framatome

ACE/ATRIUM 11 Critical Power Correlation

ANP-10335NP-A
Revision 0

Topical Report

May 2018

Framatome Inc.

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

May 25, 2018

Mr. Gary Peters, Director
Licensing and Regulatory Affairs
Framatome Inc.
3315 Old Forest Road
Lynchburg, VA 24501

SUBJECT: FINAL SAFETY EVALUATION FOR FRAMATOME INC. TOPICAL REPORT ANP-10335P, REVISION 0, "ACE/ATRIUM 11 CRITICAL POWER CORRELATION" (CAC NO. MF5841; EPID L-2015-TOP-0002)

Dear Mr. Peters:

By letter dated February 27, 2015 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML15062A553), Framatome Inc. (Framatome, formerly AREVA Inc.) submitted Topical Report (TR) ANP-10335P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation," to the U.S. Nuclear Regulatory Commission (NRC) staff for review and approval. By letter dated March 27, 2018 (ADAMS Accession No. ML18058B960), an NRC draft safety evaluation (SE) regarding our approval of TR ANP-10335P, Revision 0, was provided for your review and comment. By letter dated April 23, 2018 (ADAMS Accession No. ML18116A469), Framatome provided comments on the draft SE. The NRC staff's disposition of the Framatome comments on the draft SE are discussed in the attachment (ADAMS Accession No. ML18120A356) to the final SE enclosed with this letter.

The NRC staff has found that TR ANP-10335P, Revision 0, is acceptable for referencing in licensing applications for nuclear power plants to the extent specified and under the limitations and conditions delineated in the TR and in the enclosed final SE. The final SE defines the basis for our 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 licensing action requests, our review will ensure that the material presented applies to the specific plant involved. Requests for licensing actions 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 Framatome publish approved proprietary and non-proprietary versions of TR ANP-10335P, Revision 0, within 3 months of receipt of this letter. The approved 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 approved versions shall include an "-A" (designating approved) following the TR identification symbol.

As an alternative to including the RAIs and RAI responses behind the title page, if changes to the TR were provided to the NRC staff to support the resolution of RAI responses, and if the NRC staff reviewed and approved those changes as described in the RAI responses, there are two ways that the accepted version can capture the RAIs:

1. The RAIs and RAI responses can be included as an Appendix to the accepted version.
2. The RAIs and RAI responses can be captured in the form of a table (inserted after the final SE) which summarizes the changes as shown in the approved version of the TR. The table should reference the specific RAIs and RAI responses which resulted in any changes, as shown in the accepted version of the TR.

If future changes to the NRC's regulatory requirements affect the acceptability of this TR, Framatome will be expected to revise the TR appropriately or justify its continued applicability for subsequent referencing. Licensees referencing this TR would be expected to justify its continued applicability or evaluate their plant using the revised TR.

Sincerely,

Dennis C. Morey, Chief
Licensing Processes Branch
Division of Licensing Projects
Office of Nuclear Reactor Regulation

Project No. 728

Docket No. 99902041

Enclosure:
Final Safety Evaluation

FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT ANP-10335P, REVISION 0

"ACE/ATRIUM 11 CRITICAL POWER CORRELATION"

FRAMATOME INC.

DOCKET NO. 99902041

Enclosure

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1.0 INTRODUCTION

By letter dated February 27, 2015 (Reference 1), Framatome Inc. (Framatome) (formerly AREVA Inc.) submitted Topical Report (TR) ANP-10335P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation [(CPC)]" (Reference 2) to the U.S. Nuclear Regulatory Commission (NRC) for review and approval. The purpose of this TR is to describe the ACE/ATRIUM 11 critical power ratio (CPR) correlation for Framatome's ATRIUM 11 boiling water reactor (BWR) fuel assembly product. ACE/ATRIUM 11 is based on Framatome's experience with the previous ACE correlations for past fuel products, including ACE/ATRIUM 10 (Reference 3) and ACE/ATRIUM 10XM (Reference 4).

The complete list of correspondence between the NRC and Framatome is provided in Table 1.1 below. This includes requests for additional information (RAIs), responses to RAIs, audit documentation, and any other relevant correspondence.

Table 1.1 – List of Key Correspondence

Sender	Document	Document Date	Reference
Framatome	Submittal Letter	February 27, 2015	1
Framatome	Topical Report	February 27, 2015	2
NRC	Acceptance Letter	May 8, 2015	5
NRC	Audit Plan	October 1, 2015	6
NRC	Requests for Additional Information (RAIs)	April 11, 2016	7
Framatome	Responses to RAIs	August 11, 2016	8
Framatome	Supplement to RAI Responses	December 22, 2016	9
Framatome	Revised Supplement to RAI Responses	March 30, 2017	10
NRC	Second Round RAI	October 4, 2017	11
Framatome	Response to Second Round RAI	October 27, 2017	12
Framatome	Revised RAI Responses	January 26, 2018	13

All numbered NRC staff RAIs were included in Reference 7, with responses in Reference 8. Draft RAIs A and B are documented with Framatome's response in Reference 10. The second round RAI was asked in light of steady-state dryouts observed at a nuclear power plant in another vendor's fuel; the question is documented in Reference 11, and the response in Reference 12. Finally, the RAI responses were revised after draft limitations and conditions were sent to Framatome; the revised responses are provided in Reference 13.

2.0 REGULATORY EVALUATION

The review objective of this safety evaluation (SE) is to determine the acceptability of this CPR correlation for use in reactor safety licensing calculations. CPR correlations play an integral role in the analytical methods used to demonstrate acceptable safety margin to conditions that would lead to fuel damage during normal reactor operation and anticipated operational occurrences (AOOs). Therefore, the applicable regulations from Title 10 of the *Code of Federal Regulations* (10 CFR) are as follows:

- 10 CFR Part 50, Appendix A, General Design Criterion (GDC) 10 – *Reactor design*, as it relates to whether or not the reactor core and associated coolant, control, and protection systems are designed to include appropriate margin to assure that specified acceptable fuel design limits (SAFDLs) are not exceeded during normal operation or AOOs. The CPC is used to determine the margin to the BWR thermal-hydraulic SAFDL, which exists to prevent dryout.

- 10 CFR Part 50, Appendix A, GDC 12 – *Suppression of reactor power oscillations*, as it relates to whether or not the reactor core and associated coolant, control, and protection systems are designed to assure that power oscillations which can result in conditions exceeding SAFDLs are not possible or can be reliably detected and suppressed.

- 10 CFR Part 50, Appendix B, which requires certain structures, systems, and components – including safety analyses – to be kept under a quality assurance (QA) program that satisfies certain criteria. CPCs and the methodologies that use them must be maintained under Appendix B QA programs.

- 10 CFR 50.34, "Contents of Applications; Technical Information," which requires analyses of transients and accidents to be submitted to the NRC as part of a Final Safety Analysis Report for each plant.

- 10 CFR 50.36, "Technical Specifications," which requires licensee technical specifications to include limits (known as safety limits) on variables that are found to be necessary to reasonably protect the integrity of fission product barriers. The CPC will be used, in part, to establish such safety limits.

This SE contains the NRC staff's conclusions regarding either (a) how the applicable regulations were satisfied or (b) the compensatory actions required in order to satisfy the applicable regulations.

To ensure the quality and uniformity of NRC staff reviews, the NRC created NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports" (SRP), to guide the NRC staff in performing their reviews. Some review guidance relevant to CPR correlations may be found in SRP Section 4.2, "Fuel System Design" (Reference 134) and Section 4.4, "Thermal and Hydraulic Design" (Reference 15).

However, because this guidance is not specifically established for the review of CPR correlations, the NRC staff has undertaken an effort to generate a review framework that provides direction to the NRC staff on reviewing critical heat flux (CHF) and CPCs. This review is considered by the NRC staff to be a pilot for this review framework. The framework is in the process of being published by the NRC staff. In the meantime, discussion on the structure of the enhanced review guidance is included in this SE, and the standard to which the review was performed is included in each section of the technical evaluation.

3.0 TECHNICAL EVALUATION

The TR describes the ACE/ATRIUM 11 correlation used by Framatome to predict the CPR for ATRIUM 11 fuel. The TR provides details on the ATRIUM 11 fuel design and how it differs from the previous ATRIUM 10XM fuel, a description of the correlation and its coefficients,

assessments of the correlation against defining and validation datasets, discussion of the test bundle and testing program, and some documentation of the QA program applied during correlation development.

As discussed in Section 2.0, "Regulatory Evaluation," above, this review is considered to be a pilot for new CPR correlation enhanced review guidance currently in development by the NRC staff. This SE therefore includes background on the enhanced review guidance as well as additional background information and documentation to provide context. Section 3.1, "Review Framework for Critical Power Models," provides background on the framework used to review this CPC. Section 3.2, "Application of the Review Framework," then applies this framework to perform the review.

3.1 Review Framework for Critical Power Models

The review framework used in this review is based on an application of goal structure notation (GSN). GSN provides a way to demonstrate that a statement is true by organizing a set of supporting statements in a logic pyramid. These statements are called "Goals" and each goal is either logically decomposed into a set of simpler goals, or demonstrated to be true with some set of evidence. Goals which are not decomposed, but demonstrated to be true using evidence are called "base goals." Ultimately, the entire pyramid is supported by a set of base goals. Once the base goals are demonstrated to be true, they prove that all the goals above them are true, including the top goal.

The top goal of this review framework is as follows:

> The CHF or CPC must be acceptable for use in reactor safety licensing calculations (i.e., the correlation must be able to be trusted).

The other goals in the framework, as well as their logical organization are given in Chapter 6 of this SE. The application of the framework, where the goals are also listed, is provided in Section 3.2 of this SE, "Application of the Review Framework."

3.2 Application of the Review Framework

Framatome's ACE/ATRIUM 11 correlation was reviewed according to the review framework provided in Chapter 6 of this SE. The following section provides a summary of that framework and details the justification provided by Framatome for the base goals.

3.2.1 Experimental Data

Experimental data from the Karlstein Thermal Hydraulic Test Loop (KATHY) test facility in Karlstein, Germany was used to develop the ACE/ATRIUM 11 correlation. This same facility was also used for previous versions of the ACE correlation, as well as other thermal-hydraulic experiments including pressurized water reactor CHF correlations. This section of the SE discusses the qualification of the KATHY facility and the experimental measurements it produced for development of the ACE/ATRIUM 11 correlation.

3.2.1.1 Credibility of the KATHY facility

To assure that the experimental data are sufficiently accurate for use in a CPC, the NRC staff reviewed the credibility of the KATHY facility. This review was performed to the standards of Goals 1.1.1 and 1.1.2, which state that the facility should be described in an appropriate level of detail and appropriately validated to an external source.

3.2.1.1.1 KATHY facility description

Test Facility Description

The test facility should be described in appropriate detail and references should be provided. At a minimum, this should include a loop description, test section description, and heater rod description. A reference to any applicable documents which describe the test facility should be provided.

G1.1.1

In the initial submittal (Reference 2), Framatome identified the KATHY facility as the exclusive source of ACE/ATRIUM 11 test data and provided a description of the test section. The TR also stated that directly heated rods were used for the experiments. The test section construction is consistent with test sections used to perform critical power (CP) testing at KATHY and other facilities, and the directly heated rods are commonly used in CP and CHF testing in the industry. Additionally, NRC staff has visited the KATHY facility for audits of dryout and CHF testing in the past and are thus generally familiar with its capabilities and operational procedures.

Because Framatome did not provide detailed descriptions of the test loop or instrumentation, did not provide references to test procedures, and did not provide references to appropriate QA documentation, the NRC staff was unable to formally determine the acceptability of the facility. This information was therefore requested in RAI-SNPB-1. In response, Framatome provided the requested information, including a basic description of the test loop, test instrumentation, and data acquisition system. References to a more detailed description of the test loop and QA program were also provided. More detailed information on instrumentation, instrument calibration, and test uncertainties were provided in the responses to RAIs 10, 11, 12, and 13. Portions of this information will be discussed in more detail later in this SE.

Because Framatome provided some documentation of the test facility in the ACE/ATRIUM 11 TR and additional detail as requested in the NRC staff's RAIs, the NRC staff determined that the KATHY test facility has been described in an adequate level of detail. The NRC staff therefore concluded that Goal 1.1.1 was satisfied.

3.2.1.1.2 Description of KATHY loop test procedures

Test Procedure Description

The test procedures should be described in appropriate detail and references should be provided. This should be provided for both steady-state and transient tests. A reference to any applicable documents which describe the testing procedures should be provided.

G1.1.2

While Framatome provided some discussion of the test procedures in ANP-10335P (Reference 2), this discussion did not provide sufficient detail for the NRC staff to make a determination with regard to Goal 1.1.2. This information was therefore requested by the NRC staff in RAI-SNPB-8.

In response, Framatome provided brief summaries of the steady-state and transient test procedures, as well as references to internal Framatome documents describing the procedures in detail. For steady-state tests, [

]. Transient tests are conducted in a similar manner, [

].

The NRC staff reviewed these test procedures and found them to be similar to others known by the NRC staff to be in use in the industry. The NRC staff determined that the procedures enable Framatome to adequately capture both steady-state and transient dryout with an appropriate level of accuracy, and therefore concluded that Goal 1.1.2 was satisfied.

3.2.1.1.3 KATHY facility validation

Validated Test Facility

The results of the test facility should be demonstrated to be accurate compared to an external source.

G1.1.3

Though the KATHY facility is generally well understood by the NRC staff, as discussed in Section 3.2.1.1.1, "KATHY facility description," Framatome did not provide a comparison of the KATHY facility to an external source for validation in its initial submittal (Reference 2). This information was therefore requested in RAI-SNPB-2. In response to this RAI, Framatome provided benchmarks to two test runs at the ATLAS facility. While the results of the Framatome

tests at the KATHY facility are not exactly the same as the ATLAS results, they are essentially equivalent when differences in rod peaking and test facility design are taken into consideration.

Because the test results provided by Framatome demonstrate a favorable comparison to the ATLAS test facility, the NRC staff determined that adequate benchmarking of the KATHY facility has been demonstrated for the purposes of the ACE/ATRIUM 11 CP testing. The NRC staff therefore concluded Goal 1.1.3 was satisfied.

3.2.1.2 Reproduction of local conditions in the test section

In order to assure that the experimental data are sufficiently accurate for use in a CPC, the NRC staff reviewed the ability of the ATRIUM 11 CP tests at the KATHY facility to reproduce local conditions in the test section. This review was performed to the standards of Goals 1.2.1 through 1.2.5, which state that the facility should be capable of reproducing the bundle boundary conditions expected in a reactor, that the spacer grid and heater rod geometry should reproduce the local flow field in the production bundle, that the powers tested should reproduce the local powers expected during reactor operation, and that any differences between the test and production assemblies should be addressed.

3.2.1.2.1 Range of KATHY test experimental parameters

Range of Experimental Parameters

The ranges of the experimental parameters (e.g., pressure, powers, flow rates) should be representative of the values expected in a reactor during normal operation and AOOs. This includes radial power peaking in BWR tests.

G1.2.1

Steady-State Testing

For steady-state tests, Table 5.2 in ANP-10335P (Reference 2), provides the ranges of data taken in each of the primary test section parameters, including mass flow, pressure, inlet subcooling, maximum local peaking factor (LPF), and axial power shape. This table also provides the equivalent data ranges for the ACE/ATRIUM 10XM correlation. Overall, most of the data ranges for the new correlation compare reasonably well to those of the old correlation, and to conditions expected to be experienced during steady-state operation in a BWR.

However, the NRC staff found issues with the ranges of two of the parameters. First, the [ ] was much lower than the [ ] limit intended to be used with the correlation. This will be discussed in Section 3.2.1.2.3 of this SE, "Local powers in the ACE/ATRIUM 11 test bundle." Second, Framatome [ ]. The NRC staff found that additional justification was needed to fully support [ ] and asked Framatome to provide this justification in RAI-SNPB-3.

In response to this RAI, Framatome argued that a mechanistic correlation such as ACE/ATRIUM 11 does not need to specifically test all [ ] in order to capture

the effect of [ ] on CP and dryout location. To support this, Framatome provided demonstration analyses where CPCs using the ACE form were developed and validated for several historic fuel designs using existing databases. Originally, the correlations for the ATRIUM 10XP, 10XM, and 9B fuel designs were fitted using [ ]. The demonstration correlations created by Framatome in the RAI response were fitted to the ACE form using [ ] CP test data and validated with [ ] test data. These new correlations, developed solely on the [ ] data, generally performed as well as or better than the licensed correlations when validated against [ ], both in terms of CP magnitude and axial location prediction. Only the demonstration correlation for ATRIUM 10XM did not perform as well as the licensed one in predicting dryout location to within one spacer grid of the actual location, and even then was only slightly below the [ ] acceptance criterion Framatome applies to correlations intended to be licensed.

Overall, the data provided in the RAI response supports the conclusion that it is acceptable to fit the ACE/ATRIUM 11 correlation using only [ ] CP testing data. This is because the form of the ACE correlation has been demonstrated, in the TR and the RAI responses discussed above, to be capable of adequately modeling the effect of [ ] on the CP and dryout location, with performance that is relatively insensitive to the tested [ ]. However, the NRC staff still believes that it is impossible to eliminate all sensitivity to [ ] and that [ ] should be tested to correlate appropriate model parameters and validate the correlation's performance across the computational domain.

Transient Testing

Transient testing is also expected to cover an adequate range of BWR operating conditions and potentially limiting transients. Transient testing is discussed in Section 7.3 of ANP-10335P. In the KATHY facility, transients are tested by applying forcing functions to power, pressure, and flow; different forcing functions simulate different transients. Framatome stated that the limiting transients are load rejection without bypass (LRNB) and loss of flow events. These events were simulated in the test loop with a number of different initial powers, pressures, flows, and inlet enthalpies, as detailed in Table 7.20. Sample forcing functions for each of the key transient parameters were provided in Figures 7.18 and 7.19.

The stated purpose of the transient testing was to confirm that the steady-state ACE/ATRIUM 11 correlation is conservative when used to predict dryout as part of a transient methodology. This assumption is discussed in Section 3.2.3.1.1 of this SE, "Identification of validation data." However, the NRC staff also questioned the range of the tested transient conditions, as Framatome did not conduct transient tests at low pressures. This information was requested in RAI-SNPB-4.

In response to this RAI, Framatome reiterated the intent of transient testing for CPCs, which is to prove that they behave conservatively in transients compared to steady-state. Framatome then provided a reference to the response to RAI 16 from the ACE/ATRIUM 10 TR (Reference 3). This RAI response demonstrated that decreasing pressure in a BWR leads to increased CP. Calculations of depressurization events show that, because of increased voiding in the core that drives power to decrease, the minimum CPR (MCPR) increases throughout the transient for both mechanistic and non-mechanistic correlations. Though the NRC staff accepts that this argument would generally be true, the NRC staff does not believe that depressurization

transients could be shown to be non-limiting with respect to dryout under all circumstances. However, given the difficulty associated with testing depressurization transients in CPR testing facilities, and given that the overall purpose of transient testing is to demonstrate that the steady-state correlation is conservative when applied to transients, the NRC staff finds the range of tested transient conditions acceptable. The pressure range not covered by transient tests is adequately covered by steady-state experiments.

Thus, aside from [ ], which will be discussed in Section 3.2.1.2.3, "Local powers in the ACE/ATRIUM 11 KATHY testing," the NRC staff determined that the tested range of important parameters adequately represents the ranges expected during normal operation and AOOs. The NRC staff therefore concluded that Goal 1.2.1 was satisfied.

3.2.1.2.2 ATRIUM 11 test bundle

Prototypical Test Bundle

The grid spacers and heater rods used in the test bundle should result in the same flow field as those used in the reactor fuel bundle. At a minimum, this includes grid spacer design and axial location, rod diameter, and heated length. Typically, the grid spacers and heated rods used in the test bundle should be within the manufacturing tolerances of the grid spacers and fuel rods used in the fuel bundle in the reactor.

G1.2.2

Any differences between the test bundle and the reactor bundle should be addressed. This includes components which are not in the reactor bundle but are needed for testing purposes.

G1.2.3

In Reference 2, Framatome provided a description of the ATRIUM 11 test bundle, comparisons between the ATRIUM 11 and ATRIUM 10XM bundle designs, and comparisons between the ATRIUM 11 test and production bundles. The test bundle is prototypical of the production ATRIUM 11 assembly and contains an 11-by-11 lattice of heater rods. The fuel/heater rods are the same diameter in both the test and production assemblies. In both the test and production assemblies, [ ]. Within the heated length of the test assembly, there are [ ] spacer grids, which are of the same design as the production ATRIUM 11 assembly. These spacer grids hold the heater rods in place [ ], which itself varies axially in both the test and production assemblies.

There are several differences between the test bundle and the production bundle, which are discussed in some detail in Section 9.0 of ANP-10335P. Many of these differences are either negligible or conservative. For example, the water channel in the center of the test assembly does not contain any flow; this is conservative, because bypass flow through the water channel

would provide cooling to the adjacent subchannels, adding margin to dryout for the rods in the center of the assembly. Additionally, [

] Because none of these changes impact the geometry seen by the flow, they will have a negligible effect on the CP measurements.

The NRC staff therefore determined that any geometric differences between the test bundle and the production bundle will have negligible or conservative impact on the flow field. The NRC staff has therefore concluded that criteria Goals 1.2.2 and 1.2.3 are satisfied.

3.2.1.2.3 Local powers in the ACE/ATRIUM 11 KATHY testing

Local Powers

The local powers in the test bundle should reflect the expected local powers in the reactor assembly/bundle. This is accomplished through testing of representative axial and radial power shapes.

G1.2.4

In Reference 2, Framatome provided a discussion of the local powers tested in the development of the ACE/ATRIUM 11 correlation. Section 8.1.1 of ANP-10335P states that the purpose of varying the LPF is to "determine the dryout characteristics of a particular rod position."

Tested axial power shapes are shown in [

].

Framatome tested a wide range of radial power distributions, each of which is detailed in Figures 8.4 through 8.52 of the TR. However, despite the wide variation in radial distributions, the range of local powers (obtained by combining the axial and radial power distributions) is not sufficient to cover the intended use of the correlation. The maximum tested [ ] due to limitations with the heater rods. Framatome intends to use the ACE/ATRIUM 11 correlation [ ], which is significantly higher than the maximum tested [ ].

Because of this, the NRC staff asked RAI-SNPB-5 and RAI-SNPB-6 to clarify Framatome's implementation of the correlation for LPFs outside of the correlation and validation databases. RAI-SNPB-5 asked for further justification of the use of the correlation for [ ], while RAI-SNPB-6 asked for additional details on the [ ] applied with [ ].

Use of ACE/ATRIUM 11 at [ ]

In response to RAI-SNPB-5, Framatome provided a justification supporting the use of the correlation for [ ]. Ultimately, this justification relies on the concept that [ ]. This was shown in Figures 7 and 8 of the TR to be a reasonably accurate assumption for previous ACE correlations, based on test data from the ATRIUM 10 and ATRIUM 10XM test campaigns where [ ]. However, there are complicating factors in justifying this assumption for the ATRIUM 11 design: (1) the lattice for ATRIUM 11 is 11x11 rather than the 10x10 lattice of ATRIUM 10 and 10XM; (2) the ATRIUM 11 testing was only performed [ ]; and (3) the ATRIUM 11 data for determining [ ].

The issue of whether the behavior would be expected to be similar between the fuel designs is addressed first. [ ]

With the expectation that [ ], Framatome performed analyses to determine the potential effect on CP of extending beyond the tested [ ] for ATRIUM 11. This was done by comparing the ATRIUM 11 [ ] to that found in ATRIUM 10 and 10XM testing. As mentioned previously, the ATRIUM 11 [ ]. To provide a common basis for comparison with the legacy test data, the ACE/ATRIUM 10, 10XM and 11 correlations were used to calculate the CP for the conditions that were tested in the ATRIUM 10 and 10XM campaigns. From there, [ ] were calculated for both tested and calculated CPs for all three fuel designs across a range of mass flow rates and inlet subcooling values. In general, the data show that the [ ] for the ATRIUM 10 and 10XM fuel designs is [ ].

The ACE/ATRIUM 11 correlation's [ ] is slightly lower than that predicted for ATRIUM 10 and 10XM. In the analysis provided in the RAI response, Framatome averaged the [ ] over the range of inlet subcooling values for each mass flow rate and lattice design, for both measured and calculated CP. Framatome then compared the average calculated [ ] from ACE/ATRIUM 11 to the corresponding values for the ATRIUM 10 and 10XM designs to determine the absolute value of the maximum expected difference in [ ] between the designs. A range of these values were provided in Table 9 of the RAI response, and resulted in a maximum increased CP uncertainty of [ ]. The NRC staff performed a separate analysis using the data provided and concluded that [ ].

Both of these values are substantially smaller than the increased additive constant uncertainty applied by Framatome for [ ]. Though [ ] were calculated for [ ], Framatome conservatively applies an increased uncertainty to [ ]. The ACE correlation has [

]. This increased uncertainty applied to [ ] bounds the increased uncertainty from the analysis provided both from Framatome's and the NRC staff's analysis.

It is worth noting that though the NRC staff expects the [ ] when moving from a 10x10 lattice to an 11x11 lattice, the NRC staff does not necessarily expect that it would be the same for the different lattices. For assemblies producing the same amount of power, the average heat flux in an ATRIUM 11 bundle would be about [ ] lower than the equivalent ATRIUM 10 bundle and about [ ] lower than the equivalent ATRIUM 10XM bundle. For a given increase in [ ], the resulting increase in heat flux would therefore be about [ ] lower for an ATRIUM 11 bundle than for an ATRIUM 10XM bundle. This is anticipated to have an impact on the bundle CP and thus [ ], and though it is not clear how significant the impact is the NRC staff finds it reasonable to infer that the ATRIUM 11 bundle would be less sensitive to [ ] than the ATRIUM 10 or 10XM bundles. Thus the difference in sensitivity between ATRIUM 11 and ATRIUM 10/10XM is expected to bound any potential increase in uncertainty resulting from extrapolation beyond the [ ].

Because additional uncertainty will be applied through [ ] and because the additional uncertainty bounds the expected increase in uncertainty due to extrapolation beyond the tested [ ], the NRC staff determined that Framatome has adequately justified the use of the correlation at [ ].

<u>Derivation and Use of [ ] Uncertainty</u>

In response to RAI 6, Framatome provided the derivation of [

]

[ ]

[

]:

[ ]

[ ]:

[ ]

[ ]:

[ ]

[ ]

[ ]

[ ]

The NRC staff examined the data provided and found no significant trends in either bias or uncertainty with respect to [ ]. This suggests that even though the [ ], the increased uncertainty applied to [ ] has been reasonably justified for application beyond the tested range. Considering, too, [ ], the NRC staff determined that there is reasonable assurance that the increased uncertainty will bound the expected uncertainty for [ ].

Though the tested range of local powers does not necessarily completely cover the expected range of local powers, the NRC staff determined that the range of tested local powers is acceptable because adequate justification has been provided for the use of the correlation beyond the tested range, in part because an increased uncertainty will be applied to highly peaked bundles (which are also unlikely to be limiting). In their justification, Framatome ultimately provided reasonable assurance that the prediction of CPs in determination of the safety limit will be appropriately conservative. The NRC staff has therefore concluded that criterion 1.2.3 has been satisfied.

3.2.1.2.4 Part length rods in the ACE/ATRIUM 11 test bundle

> **Part length or Unheated Rods**
>
> Any part length or unheated rods in a reactor bundle should be accurately reflected in the test bundle. Additionally, any part length rods should have the same heated length in both the reactor and test bundles.
>
> G1.2.5

As discussed in Section 3.2.1.2.2, "ATRIUM 11 test bundle," there were several minor geometric differences between the ACE/ATRIUM 11 production and test bundles. These differences were found above to have negligible impact on the flow field seen in the test section, which is expected to accurately reflect the flow field in production fuel assemblies.

There were, however, differences between the test and production bundles that could have an impact on the CP measurements used to develop the ACE/ATRIUM 11 correlation. Though the PLRs are the same length in both the production and test assemblies, the heated length is not exactly the same. In the production bundle there is a short, unheated plenum at the bottom of the bundle. In the test bundle the PLR beginning of heated length was [ ].

Framatome argued in Section 9.0 of ANP-10335P that [ ]. However, the NRC staff believed that the difference would potentially result in a difference between the k-factors seen in the test bundles versus those expected in equivalent production bundles. The NRC staff therefore requested additional justification of these differences in RAI-SNPB-7.

In response, Framatome replied that the [ ] different from the production assembly and that the physical geometry was otherwise identical, leading to identical flow areas and distribution. Framatome argued that [ ] has no impact on the correlation. The argument is that the [ ]. Ultimately, the NRC staff believes that the [ ] will be mostly accounted for directly by the correlation and that, because of the magnitude of the difference, any impact should be so small as to be essentially irrelevant.

Because the axial location of heat input into the subchannel is directly accounted for in the correlation and the difference in heated length between the test and production assemblies is so small, the NRC staff has determined that the treatment of part length rods in the test assembly adequately replicates the production assembly for the purposes of CP measurement. The NRC staff therefore concluded that Goal 1.2.5 was satisfied.

3.2.1.3 Measurement Accuracy

Beyond faithfully reproducing the local conditions in the test section, CP tests must provide accurate measurements of tested parameters. The accuracy of the measurements taken at a test facility is influenced by the test procedures, experimental design, and the instrumentation itself. The review was therefore performed to the standards of Goals 1.3.1 through 1.3.6. Goals 1.3.1 through 1.3.6 state that the facility should employ appropriate test procedures and statistical design of experiments; that the instruments used in testing should have reasonably low uncertainty; that the instrumentation should be diverse, redundant, and appropriately calibrated; that the test facility should quantify the uncertainty in the measured CP; and that heat losses in the test section should be quantified and found to be appropriately low.

3.2.1.3.1 KATHY loop measurement uncertainties

Measurement Uncertainties
The measurement uncertainties of all measured parameters and other variables important to the CHF or CPC should be reasonably low.
G1.3.1

The measurement uncertainties of the KATHY facility were briefly mentioned in ANP-10335P (Reference 2) [ ]. However, the actual values of the uncertainties and how they were derived were not discussed in the TR. The NRC staff therefore asked RAI-SNPB-10 to obtain additional information about the measurement uncertainties.

In response, Framatome detailed the measurement uncertainties for mass flow rate, pressure, inlet subcooling, test assembly power, and LPF, as well as the equipment and standards used to determine them. The NRC staff reviewed these uncertainty values and determination methods and has determined that the measurement uncertainties for the ACE/ATRIUM 11 CP experiments were reasonably low. The NRC staff therefore concluded that Goal 1.3.1 is satisfied.

3.2.1.3.2 Diversity and redundancy of KATHY loop measurements

Diverse and Redundant Measurements
Important experimental parameters (e.g., pressure, flow, temperature, and power) should have diverse and redundant means of experimentally measuring their values.
G1.3.2

Framatome's original submittal (Reference 2) did not provide any significant discussion of the KATHY facility instrumentation. The NRC staff therefore requested this information in RAI-SNPB-11.

In response, Framatome provided the requested discussion of instrumentation redundancy and diversity. [

] Bundle power is taken as the product of the voltage and current measurements, [

]. The types of instrumentation discussed in the RAI response are expected to be sufficiently diverse and redundant for the key parameters used to correlate and validate the CPC. The NRC staff therefore concluded that Goal 1.3.2 is satisfied.

3.2.1.3.3 KATHY loop instrument calibration

Instrument Calibration
The instrumentation should be repeatedly calibrated and checked to ensure accurate measurements.
G1.3.3

Framatome's original submittal (Reference 2) provided no substantial discussion of the KATHY facility instrument calibration process. The NRC staff therefore requested this information in RAI-SNPB-12.

In response, Framatome provided a brief discussion of the calibration process and references to calibration procedures for the various types of instruments used at the facility. Calibration is performed within a controlled calibration lab on a [

]. The NRC staff determined that the calibration of the KATHY loop instrumentation as described in the RAI response was appropriate, and therefore concluded that Goal 1.3.3 was satisfied.

3.2.1.3.4 Method for determining dryout in KATHY critical power testing

Method for Determining Dryout
The method for determining departure from nucleate boiling (DNB) or dryout should ensure an accurate capture of the CHF or CP. This method includes the testing procedures used to take a single data point and the criteria used to determine that DNB or dryout has occurred. This includes the stability conditions and the procedure for approaching DNB or dryout. This should be provided for both steady-state and transient tests as the tests often have different testing procedures and may have different criteria for determining whether a critical boiling transition has occurred.
G1.3.4

The NRC staff dispositioned this Goal in Section 3.2.1.1.2, "Description of KATHY loop test procedures," which discussed the procedures used to take a single datapoint. These procedures included the criteria used to determine when dryout occurred in testing and the stability condition and processes used when approaching dryout. The NRC staff thus concluded that Goal 1.3.4 was satisfied.

3.2.1.3.5 KATHY critical power measurement uncertainty

Experimental Uncertainty
The CHF or CP experimental uncertainty should be quantified by determining the variance of the CHF or CP measurement through test repetition. This error should be small when compared with the uncertainty in the correlation.
G1.3.5

In the original submittal (Reference 2), Framatome did not provide a discussion of the uncertainty associated with an experimental measurement of CP. Though Framatome alluded to test repetition in Section 8.1.3, it was not discussed in any detail and the CP measurement uncertainty was never quantified. The NRC staff therefore asked RAI-SNPB-13 to obtain this information.

In response, Framatome provided an analysis of the [ ] from the ATRIUM 11 CP test campaign to quantify the CP measurement uncertainty. The overall steady-state CP measurement uncertainty was found to be [ ]. The uncertainty of transient CP measurements [ ].

The NRC staff determined that the CP measurement uncertainty was well characterized and appropriately low, and finds it acceptable to [ ]. The NRC staff therefore concluded that Goal 1.3.5 was satisfied.

3.2.1.3.6 Characterization of KATHY loop heat losses

> **Heat Losses from the Test Bundle**
>
> Heat losses from the test bundle should be well characterized.
>
> G1.3.6

In the original submittal (Reference 2), Framatome did not discuss the heat losses from the test section of the experiment. Because these losses effectively define the fraction of the heater rod power that is deposited in the coolant, it is critical that these heat losses be understood. The NRC staff therefore asked RAI-SNPB-14, to understand how the heat losses in the test section have been characterized and appropriately considered.

In response, Framatome provided a description of the bundle test section of the KATHY loop and some analyses of the heat losses. The bundle test section consists of a liner, in which the bundle sits, [ ].

Heat losses from the test section are characterized as [ ]. Heat balance measurements are performed at the beginning of each testing day to determine the losses through the test section. Heat losses have also been analytically evaluated. Overall, though the heat losses [ ], the measurements taken during the ATRIUM 11 testing campaign have a mean of [ ] and a standard deviation of [ ]. This puts heat losses in the test section at roughly the same order of magnitude as [ ]. Framatome considers them to be negligible.

The NRC staff does not agree with Framatome description of the heat losses as negligible, considering that they can potentially be on the order of a percent of the lowest CP measurements in the database and represent a persistent non-conservative bias on the CP measurement. However, the NRC staff also determined from the information provided that the test section heat losses were well characterized by Framatome based on the testing.

In Framatome's revised RAI response in Reference 13, Framatome indicated that the bias that results from the heat losses is [

]. As such, the NRC staff is satisfied that bias in the CP measurements induced by heat losses is appropriately accounted for. Additionally, Framatome stated in the revised RAI response that [

]

Considering that the heat losses are small, [

], the NRC staff determined that G1.3.6 was satisfied.

3.2.2 Correlation Generation

Though the majority of the Goals governing the NRC staff's review of CPCs are based on the performance of the testing facility or the correlation itself, the correlation must also be generated in a logical, reasonable way. This ensures that the physical behavior of the correlation is consistent across the application domain, and helps the NRC staff to understand the correlation and the assumptions that underpin it.

3.2.2.1 Appropriate Mathematical Form

In general, the correlation is expected to have an appropriate mathematical form. Major relevant parameters should appear as variables – in the case of CPCs, this includes pressure, mass flow rate, and quality. The behavior of the correlation with respect to these variables should be consistent with known behavior. The NRC's review in this area was therefore performed to the standards of Goals 2.1.1 and 2.1.2, which state that the correlation's form should contain all necessary parameters and that the reasoning for the choice of mathematical form should be discussed and logical.

3.2.2.1.1 Variables of the ACE/ATRIUM 11 correlation

Correlation Variables
The mathematical form of the model contains all necessary variables.
G2.1.1

In Reference 2, Framatome stated that the form of the ACE/ATRIUM 11 correlation was unchanged from the form of ACE/ATRIUM 10. Section 6 of ANP-10335P, which describes the correlation form and the coefficients, refers to Appendix A of the ACE/ATRIUM 10 TR (Reference 3) for a complete derivation of the form.

The major variables used in the correlation are:

- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]

Though this is not an exhaustive list, these variables generally have the most significant impact on the CP prediction. Other factors used in the correlation are generally constants.

The variables listed above correspond with the variables of primary importance in determining the CP, based on the NRC reviewers' experience. As such, the NRC staff determined that Goal 2.1.1 was satisfied.

3.2.2.1.2 Mathematical form of the ACE/ATRIUM 11 correlation

Mathematical Form of the Correlation
The reasoning behind the mathematical form of the correlation should be discussed.
G2.1.2

As discussed in Section 3.2.2.1.1, "Variables of the ACE/ATRIUM 11 correlation," the form of the ACE/ATRIUM 11 correlation is unchanged from the form of ACE/ATRIUM 10. The ACE/ATRIUM 11 correlation is [ ]

This correlation form provides a mechanistic treatment of boiling transition. It is also worth noting that the form of the ACE/ATRIUM 11 correlation includes a k-factor that [ ]. This is different from the original forms of the ACE/ATRIUM 10 and 10XM correlations, which have been updated since their initial NRC approval to include the same feature. Overall, though, the form of the correlation is the same as in the previously-approved ACE correlations and continues to be considered by the NRC staff to be appropriate.

The NRC staff was not able, however, to determine the reasoning behind the choice of the initial and boundary conditions selected for the ACE/ATRIUM 11 correlation, especially including the initial condition for [ ]. The NRC staff therefore asked for this information in RAI 15.

In response, Framatome provided a discussion of the correlation's initial and boundary conditions, with a particular emphasis on [

]. Since the value meets the physical needs of the mechanistic correlation and otherwise results in reasonable CP predictions when the model is applied, the NRC staff found it to be acceptable.

Because Framatome was able to demonstrate the appropriateness of the correlation's initial conditions, the NRC staff determined that the correlation form, including initial and boundary conditions, was appropriate. The NRC staff therefore concluded that Goal 2.1.2 was satisfied.

3.2.2.2 Appropriate Coefficients

In order to ensure that the correlation's coefficients were chosen properly, the NRC staff reviewed both the data used for determining the coefficients and the method used for determining the coefficients from the data. This review was performed to the standards of Goals 2.2.1 through 2.2.3. Goals 2.2.1 through 2.2.3 state that the data used to generate the correlation (the "training data") should be identified; that the method for calculating the coefficients should be described; and that the method for calculating the k-factors and additive constants should be described, with particular emphasis on the method employed to determine additive constants for rods that do not experience dryout in testing.

3.2.2.2.1 Identification of training data

Identification of Training Data
The training data (i.e., the data used to generate the coefficients of the correlation) should be identified.
G2.2.1

In Reference 2, Framatome stated that approximately [ ] of the data were used as training data for the correlation. This correlating data set explicitly excluded the [ ] data points, which were used to validate the correlation's performance. Though the training data points were not individually identified, plots of ECPR versus each of the key parameters were provided for the training data in Section 7.1 of ANP-10335P.

Framatome broke the data into correlating and validating datasets for the purposes of fitting the [ ] as well as the additive constants. As will be discussed in Section 3.2.3.3.1, "Calculation of correlation statistics," Framatome's response to RAI-SNPB-28 stated that it was necessary to [ ]. Section 3.2.3.1.1, "Identification of validation data," also discusses Framatome's response to RAI-SNPB-19, which demonstrated that the correlation is relatively insensitive to the choice of correlating and validating data. This led the NRC staff to find it acceptable to use [ ] for the purpose of determining the correlation statistics.

The NRC staff determined based on the above that the training data was identified appropriately and thus concluded that Goal 2.2.1 was satisfied.

3.2.2.2.2 Coefficient calculation

Calculation of the Correlation's Coefficients

The method for calculating the correlation's coefficients should be described.

G2.2.2

Though Framatome identified all of the fitted coefficients in Section 6 of the original submittal (Reference 2), the TR provided very little information about how the coefficients were calculated. The NRC staff therefore requested this additional information in RAI-SNPB-16.

In response, Framatome provided a brief description of the correlation fitting and assessment process, as well as a reference to Appendix A of the ACE/ATRIUM 10 TR, which describes the correlation derivation and the fitting process in detail. A set of **[** **]** is chosen and assessed for suitability by examining correlation prediction statistics, trends in predictive capability with respect to key parameters, and **[** **]**. This process is repeated until the results are satisfactory. Once a set of **[** **]** has been chosen, **[** **]** are fitted using **[** **]**. Additive constants are then fitted, and will be discussed below in Section 3.2.2.2.3, "Calculation of k-factors and additive constants."

Framatome assesses the correlation behavior **[** **]**.

The NRC staff determined that the method used to calculate the correlation's coefficients is appropriate because the appropriate mechanistic behavior of the correlation will be assured while minimizing error in the prediction. The NRC staff therefore concluded that Goal 2.2.2 is satisfied.

3.2.2.2.3 Calculation of k-factors and additive constants

Calculation R or K Factors and Rod Constants

The method for calculating the R- or k- factors and the additive constants (for both full length and part length rods) should be described. Further, a description should be provided of how these values are calculated if dryout is not measured on the rod under consideration **(CP only)**.

G2.2.3

In Reference 2, Framatome provided a detailed discussion of the method used to calculate the k-factors and additive constants. The **[** **]** and is calculated for a given rod based on **[**

].

The additive constant for each rod, l_i, is based on [

]

From the discussion in Section 6.10, the NRC staff was largely able to assess the adequacy of the proposed k-factor and additive constant fitting process. However, the NRC staff had questions regarding the [
] and the [
]. The NRC staff therefore asked RAI-SNPB-17 and RAI-SNPB-18 to obtain this information.

In response to RAI-SNPB-17, Framatome stated that [

]. The NRC staff finds this to be appropriate in the context of the ACE CP model.

In response to RAI-SNPB-18, Framatome provided additional information on the [ ]. This adjustment was performed to account for the fact that insufficient data was taken in STS119.01A to determine the [ ] to a degree of precision that Framatome considered adequate. In calculating the adjustment, Framatome first determined the number of datapoints required for adequate precision. Framatome then calculated a 95 percent confidence interval for the mean value of the [ ] based on that number of datapoints and the standard deviation of the total population of additive constants. This provided an interval for the mean value of the [ ] that would be expected if a sufficient number of datapoints had been collected. Framatome subsequently calculated the same interval, assuming the actual number of datapoints that were collected. The mean value of the additive constant was then adjusted such that the upper bound of the interval with more data would match the upper bound of the interval with less data. This results in the same upper limit for [ ].

The purpose of the adjustment is to allow an additive constant penalty to be applied to [ ]. This is desirable for Framatome because such a penalty, if applied to [ ], would introduce an overly conservative bias for [ ]. Assessments performed in Table 14 of the RAI response confirm that [ ]. The NRC staff were therefore able to determine that the additive constant penalty was reasonable, in that it resulted in the same [ ], and was shown to result in a conservative prediction of CPR as compared to the experiment.

Ultimately, the NRC staff was able to conclude that the process used to calculate the additive constants was appropriate. Each rod position was adequately represented in the data and appropriately accounted for in the process. The means by which the additive constant was calculated for rods that did not experience dryout in testing is such that a conservative determination of the CP is expected to result. The PLR additive constants were found to be reasonable and are also expected to result in conservative predictions of the CP. The NRC staff therefore determined that Goal 2.2.3 is satisfied.

3.2.3 Correlation Validation and Uncertainty Quantification

The following sections will discuss the validation and uncertainty quantification performed by Framatome for the correlation, including discussions of the validation data that was used, the range over which validation data exists, the range where the correlation is intended to be used and how it is restricted to that range, the distribution of data in the expected domain, and the design of experiments used in the correlation.

3.2.3.1 Appropriate Distribution of Validation Data

In order to assure that the validation of the ACE/ATRIUM 11 correlation was adequate, the NRC staff reviewed the partitioning of the data into calibration and validation datasets, as well as the range over which the correlation is intended to be used. In that range, the NRC staff additionally reviewed the distribution of the data to determine whether sufficient data was present to constitute appropriate validation. Finally, the NRC staff reviewed the design of experiments for the ACE/ATRIUM 11 testing at the KATHY facility to determine whether the testing was appropriately randomized to remove any systematic error from the validation data. This review was performed to the standards of Goals 3.1.1 through 3.1.7, and will be discussed in the following sections.

3.2.3.1.1 Identification of validation data

Identification of Validation Data
The validation data (i.e., the data used to quantify the correlation's error) should be identified and should be separate from the training data.
G3.1.1

In the original submittal (Reference 2), Framatome stated that approximately [ ] of the data were used as validation data for the correlation. The validation data set explicitly included the [ ] data points. The correlation was also validated by comparison to transient CP measurements, which is discussed in Section 7.3 of ANP-10335P. Though the validation data points were not individually identified, plots of ECPR versus each of the key parameters were provided for the validation data in Section 7.2 of ANP-10335P.

As was discussed in Section 3.2.2.2.1 of this SE, "Identification of training data," it was revealed that though the data was partitioned into correlating and validating datasets for the purposes of fitting [ ]. This will be discussed in additional detail in Section 3.2.3.3.1, "Calculation of correlation statistics."

Table 7.13 of ANP-10335P shows that the data from [ ]. The NRC staff was concerned that the choice of [ ] would potentially have an impact on the correlation uncertainty, and asked RAI-SNPB-19 to understand these effects in more detail.

In response to this RAI, Framatome provided a discussion of their correlation development guideline and its requirements for data partitioning. According to the guideline, [ ] of the data is randomly selected to be in the defining dataset and the remaining [ ] is reserved for validation. However, if there are fewer than $2p + 25$ datapoints (where p is the number of coefficients being fit in the correlation), Framatome does not partition the dataset – this is consistent with the recommendations of NUREG/CR-4604, "Statistical Methods for Nuclear Material Management," Section 6.4.7. This has implications for [

], as will be discussed in additional detail in Section 3.2.3.3.1, "Calculation of correlation statistics."

In addition to this discussion of the development requirements, Framatome also provided analyses where the data was randomly repartitioned [

] Ultimately, the choice of different data partitions had extremely minimal impacts on the ECPR mean and standard deviation and the additive constant uncertainty. Because Framatome was able to demonstrate this stability in the CPC, the NRC staff determined that the choice of validation data has a negligible impact on the CPC uncertainty.

The NRC staff determined from Framatome's RAI response that the correlation is relatively insensitive to the choice of correlating and validating data, which is one of the NRC staff's primary concerns in reviewing empirical correlations. The NRC staff therefore concluded that Goal 3.1.1 was satisfied, in that all validation data was appropriately identified.

3.2.3.1.2 Identification of the computational domain

Identification of the Computational Domain

The computational domain of the correlation should be mathematically defined.

G3.1.2

In Table 2.1 and Section 6.13 of the original submittal (Reference 2), Framatome defined the computational domain of the ACE/ATRIUM 11 correlation as follows:

Table 3.1 – Range of applicability of the ACE/ATRIUM 11 correlation from ANP-10335P.

[ ]

Because the computational domain was identified, the NRC staff concluded that Goal 3.1.2 was satisfied.

3.2.3.1.3 Restriction of calculation to the computational domain

Restricted to the Computational Domain
It should be ensured that the correlation will not be used outside of the computational domain.
G3.1.3

Section 6.13 of Framatome's original submittal (Reference 2) discusses the range of each of the parameters and how it is ensured that the correlation is applied within that range. [ ] is straightforward, with the calculated CP considered to be invalid if the bounds discussed in Section 3.2.3.1.2 are exceeded.

[ ] is also relatively straightforward. Framatome states in Section 6.13.3 of ANP-10335P that the ACE/ATRIUM 11 correlation [ ]. This precludes [ ]. The [ ] is also checked directly against the maximum of the range discussed in Section 3.2.3.1.2, "Identification of the computational domain." If the value exceeds the maximum, it is [ ]. While this does not necessarily ensure that the correlation would not be used outside of the computational domain, the NRC staff considers this to be conservative based on [ ] as demonstrated in the ACE/ATRIUM 11 TR.

If the [nodal mass flow] for the correlation exceeds [ ], the code [ ]. Again, while this does not necessarily ensure that the correlation would not be used outside of the computational domain, it does, by definition, result in a conservative prediction of CP and is therefore acceptable.

Framatome does not apply [ ]. However, since [ ], it was unclear to the NRC staff how the ACE/ATRIUM 11 correlation [ ]. The NRC staff therefore asked RAI-SNPB-21 to ascertain [ ]. Framatome responded [ ]. As will be discussed in Section 3.2.3.1.4, "Sparse regions in the computational domain," use of the correlation [ ] is expected to be unconditionally conservative.

The NRC staff was also unable to identify from the TR how Framatome proposed to limit the correlation to [ ]. The NRC staff therefore asked RAI-SNPB-22 and RAI-SNPB-23 to determine how Framatome will ensure the correlation is applied in the appropriate range.

In response to RAI-SNPB-22, Framatome stated that [

]. This will ensure that application of the correlation to [ ] will be conservative.

The NRC staff is thus satisfied that the correlation will not be used at [ ] and that application of the correlation to [ ] will be either conservative or will have no impact on the MCPR evaluation. When combined with the other conclusions in this section regarding pressure, inlet subcooling, and mass flow rate, the NRC staff therefore concluded that Goal 3.1.3 is satisfied.

3.2.3.1.4 Sparse regions in the computational domain

Sparse Regions in the Computational Domain

The expected domain of the correlation should be appropriately defined and justified. At a minimum, the input variables should be compared two at a time using a two-dimensional (2-D) plot with input variable 1 on the x-axis and input variable 2 on the y-axis. Each plot should display the validation data, as well as expected domain for that variable combination and some justification of that expected domain. Any anticipated new regions of application should be discussed.

G3.1.4

Empty regions of the expected domain should be justified to be unconditionally conservative.

G3.1.5

The data should be well distributed throughout the expected domain with a sufficient density.

G3.1.6

In reviewing Framatome's initial submittal (Reference 2), the NRC staff determined that there was insufficient information to make a conclusion regarding Goals 3.1.4 through 3.1.6. The NRC staff therefore asked RAI-SNPB-24 to obtain plots of the computational domain from Framatome.

In response, Framatome provided plots of the computational domain in all combinations of the key input parameters of [ ]. The NRC staff examined these plots to identify data-sparse regions and determine if they presented any concerns.

[ ] data extends well beyond the intended application of the model to the edges of the computational domain. It is taken in narrow bands around [ ], with significant gaps in between the bands. Given, however, that there are no trends in the ECPR bias as a function of [ ], and that the calculated CP is not a strong function of [ ], the NRC staff believes that interpolation between these data bands is appropriate.

[ ] data extends above the intended range of application of the model to the edge of the computational domain; however, it does not extend to [ ]. At [ ] the correlation is expected to be unconditionally conservative. As discussed in Section 6.13.1 of the ACE/ATRIUM 11 TR, this is because the correlation [ ].

The bulk of the [ ]. Very low [ ] does not exist. Some very high [ ]. The NRC staff accepts this justification, since the data at [ ] is very conservatively predicted, as shown in Figure 7.12 in the ACE/ATRIUM 11 TR. Though there is extrapolation beyond the data at [ ], the correlation is not particularly sensitive to this parameter and the extrapolation is relatively small. Additionally, there is a requirement in the correlation's implementation for [ ]. Because of this, the NRC staff determined that the extrapolation is acceptable, and any error introduced by the extrapolation would be smaller than the correlation's uncertainty.

In terms of [ ], the bulk of the data is roughly between [ ]. The intended range of application is from roughly [ ], so there are substantial gaps at both the upper and lower ends of the range. The upper end of the range is discussed in Section 3.2.1.2.3, "Local powers in the ACE/ATRIUM 11 KATHY testing." There is no limit on applicability at the low end of [ ]. The lower end of the range of expected application, however, is anchored by a number of data points [ ], so it is interpolation rather than extrapolation. When examined in terms of [ ], there is less spread in the data and thus the interpolation does not appear to be significant. Since the correlation uses the [ ] as a correlating variable, this is an important distinction.

As expected, and consistent with other approved critical boiling transition correlations, there are gaps in the dataset. However, the interpolation distance is generally reasonable and, because there are no trends in ECPR with respect to any of the key parameters it is acceptable. In general, data exists in the computational domain outside of the intended application domain and thus extrapolation beyond test data is only done in limited circumstances where it is either considered unconditionally conservative to do so or is near data. Circumstances of extrapolation or significant interpolation were discussed earlier in this section and are considered by the NRC staff to be adequate. The NRC staff therefore determined that the

sparse regions within the computational domain were properly identified and appropriately justified, and thus concluded that Goals 3.1.4, 3.1.5, and 3.1.6 were satisfied.

3.2.3.1.5 Design of ACE/ATRIUM 11 critical power experiments

Statistical Design of Experiments

Ideally, the experimental input conditions would be randomized during each run, but this is impractical due to testing considerations. Therefore, some method of ensuring that the experimental data taken is independent of any bias due to similar input conditions should be demonstrated. Further, input conditions which can be randomized should be.

G3.1.7

Framatome provided some discussion of the design of experiments for the CP testing in Section 8 of ANP-10335P (Reference 2). **[**

].

The procedure discussed by Framatome in the TR does not, however, demonstrate that the data taken is independent of bias caused by lack of randomization in the input conditions. The NRC staff therefore asked RAI-SNPB-9 to obtain additional information about the experimental design. Framatome responded with a detailed discussion of the way CP test campaigns are designed to provide sufficient data for correlation/validation and small biases. Several types of tests exist, including:

- standard map tests, which test **[** **]**;
- statistical design of experiments (SDE) tests, which test **[** **]**;
- full map tests, which test **[** **]**; and
- partial map tests, which **[** **]**.

All of the tests, aside from the partial map tests, **[** **]**.

Because Framatome takes **[** **]**, the NRC staff has determined that **[**

]. The NRC staff has therefore concluded that Goal 3.1.7 is satisfied.

3.2.3.2 Validation Error Inconsistencies

The NRC staff also reviewed the validation data to ensure that it did not contain non-poolable datasets or non-conservative subregions. This review was performed to the standards of Goal 3.2.1 and Goal 3.2.2.

3.2.3.2.1 Identification of non-poolable datasets

Identifying Non-Poolable Data Sets

The validation error should be investigated to determine if it contains any sub-groups which are obviously not from the same population (i.e., not poolable).

G3.2.1

Section 7.0 of the original submittal (Reference 2) provides a statistical analysis of the defining and validating datasets. Plots are given of the ECPR as a function of mass flow rate, pressure, axial power shape, inlet subcooling, and k-factor, as well as calculated CP versus measured CP. Tables are also provided with the data binned into groups.

From these tables and plots, the NRC staff determined that there were several groups of data that required further investigation to determine whether or not they were poolable. First, [ ]. In the validating dataset, the [ ] bin, centered around [ ], has [ ]. The NRC staff did not believe Framatome's justification, that the trend was the result of testing, was sufficient. The NRC staff therefore asked RAI-SNPB-25 to obtain further discussion on the subject from Framatome.

In response (Reference 8), Framatome stated that the apparent increase in ECPR standard deviation was a result of increasing standard deviation in [ ] – in particular, tests [ ] displayed this behavior. The NRC staff investigated the data from these particular tests at [ ] to determine if they could be pooled with the rest of the data. A Kolmogorov-Smirnov test (performed with the null hypothesis that the distribution of the data was the same, and an acceptance criterion of 0.05) demonstrated that the data [ ] was not statistically distinguishable from the rest of the CP data. The NRC staff concluded from similar statistical testing, and by examining various plots, that data from [ ] did not come from the same population as the rest of the data. While the data from [ ] also could not pass the same test, the NRC staff plotted this data and observed that the empirical cumulative distribution function (ECDF) is comparable to that of the rest of the dataset – see Figure 3.2 below. Any failures on statistical tests [ ] are likely due to the fact that there are only [ ] datapoints at [ ]. Thus, the data from [ ] appear in general to be poolable with the rest of the CP data, the data from [ ] are not necessarily so.

[ ]

Figure 3.2 – A comparison of the ECPR distribution functions between [ ].

After thoroughly reviewing the available CP testing data, the NRC staff agrees with Framatome's conclusion that the increased variance in the ECPR at [ ] is the result of [ ]. Several [ ] have higher than expected variance (when binned by [ ]), and the mean ECPR of these tests also diverge from the overall mean of the ECPR distribution as [ ] increases. Table 16 in Framatome's RAI response which bins the ECPR by [ ] demonstrates this very well. Regardless of whether the ECPR variance is in line with the overall variance, most of the individual bins have means that deviate substantially from unity. This is illustrated in Figure 3.3 below, which shows the ECDFs of ECPR broken down by test series [ ]. On both plots, the black line is the ECDF of all of the CP data from the ATRIUM 11 testing. As can be seen in the plots, the data tends to move farther away from the nominal distribution as [ ].

[ ]

Figure 3.3 – ECDFs of ECPR grouped by test at selected pressures.

The data does not appear to be poolable between tests at [ ]. Framatome's response to RAI 27, however, stated that [ ]. As stated slightly differently in response to RAI 26: "The essential uncertainty of the dryout correlation that goes into the safety limit methodology and calculation is [ ]" This aspect of the [ ] is explained in additional detail in Section 6.10 of the TR (Reference 2), and particularly in equations 6.38 and 6.39.

However, as will be discussed later in Section 3.2.3.3.1, "Calculation of correlation statistics," equation 6.38 assumes that the populations being combined have the same underlying variance but different means. This is not the case for the data at [ ], where the different test populations have statistically distinguishable means and variances. As such, the NRC staff believes that there is data at [ ] that is not poolable with the rest of the data, and that it represents a non-conservative subregion. The issue of whether this data is a non-conservative subregion will be discussed in Section 3.2.3.2.2, "Identification of non-conservative subregions," and the issue of whether the correlation uncertainty must be adjusted to account for this region will be discussed in Section 3.2.3.3.1, "Calculation of correlation statistics."

Based on the plot of ECPR as a function of [ ] in Figure 7.6, the NRC staff was concerned both that the data was not poolable and that the [ ] bins provided in [ ] did not correctly represent the data. In response to SNPB-RAI-26, Framatome provided a plot of ECPR as a function of [ ] to demonstrate that there is less variability in [ ] than in [ ], which occurs in part because [ ]. This RAI response also addressed the issue that the NRC staff had with the [ ] bins provided in [ ], which did not appear to be a natural match for the plot

provided in [ ]. As discussed in Framatome's RAI response, the bins were selected to be [ ] in width, with each [ ]. This accounts for the apparent odd structure of the bins relative to the plotted data.

In conclusion, the NRC staff identified sub-groups in terms [ ] that were potentially non-poolable with the rest of the data. Framatome's RAI responses indicate that

]. The [ ] is true to a certain extent; however, the equation used by Framatome to combine populations assumes that they have the same variance and different means. As such, the regions identified at [ ] that were found to not be poolable with the rest of the data will be addressed in additional detail in Sections 3.2.3.2.2, "Identification of non-conservative subregions," and 3.2.3.3.1, "Calculation of correlation statistics." Because non-poolable regions were identified, the NRC staff concluded that Goal 3.2.1 was satisfied.

3.2.3.2.2 Identification of non-conservative subregions

Identifying Non-Conservative Subregions
The expected domain should be investigated to determine if contains any non-conservative subregions.
G3.2.2

The NRC staff identified one obvious non-conservative subregion in the ACE/ATRIUM 11 correlation application domain in Reference 2. In Figures 7.1 and 7.9 of ANP-10335 P, between [ ], the predicted CP non-conservatively exceeds the measured CP for all the data points. Additionally, Figures 7.3 and 7.11 indicate the potential for another non-conservative subregion at [ ], in the region that was discussed as non-poolable in Section 3.2.3.2.1, "Identification of non-poolable datasets," of this SE.

In Framatome's response to RAI-SNPB-27, all of the points in the [ ] range were found to be from [ ]. The NRC staff investigated these points further and found that they were all also [ ]. Thus, the [4.5 to 6 MW] non-conservative subregion is a subset of what must be considered for the [ ] subregion.

To determine whether or not the regions were truly non-conservative, the NRC staff applied the test suggested by Kaizer (Reference 16). This test first requires a one-sided 95/95 upper tolerance limit on the ECPR distribution to be calculated; this was found to be [ ] based on the combined dataset, assuming normality (which is well justified for the combined dataset, as discussed in the TR). Then, tests that took data at [ ] were examined to determine the number of points that exceeded the 95/95 limit. A binomial distribution was used to calculate the probability of the reported number of points exceeding the limit, given that there should only be a 5 percent rate of exceedance overall. This data is presented below in Table 3.1.

Table 3.1 – Probabilities of data clusters that exceeded the 95/95 upper tolerance limit on the combined dataset

[ ]

Thus, the NRC staff concluded that data from [ ] forms non-conservative subregions [ ]. The NRC staff considers Goal 3.2.2 to be satisfied because it focuses on identifying the non-conservative subregions; the issue of how to appropriately deal with these non-conservative subregions will be discussed below in Section 3.2.3.3.1, "Calculation of correlation statistics."

3.2.3.3 Conservative Correlation Statistics

The NRC staff reviewed Framatome's proposed correlation statistics in order to ensure that they appropriately represented any biases and uncertainties in the correlation's calculation of CP. The generation of appropriate biases and uncertainties is of particular importance for CPCs because these uncertainties are directly used in calculation of the MCPR safety and operating limits. This review was performed to the standard of Goal 3.3.1, which states that the correlation statistics should reflect any changes needed to make the prediction conservative overall.

3.2.3.3.1 Calculation of correlation statistics

Calculation of the Correlation Statistics

The calculation of the correlation statistics should reflect any changes deemed necessary to generate a conservative correlation statistic.

G3.3.1

<u>Steady-State Applications</u>

In Reference 2, Framatome discussed several correlation statistics, including ECPR mean and standard deviation for the correlating dataset, validating dataset, and combined dataset; additive constant statistics were also discussed. The [ ] were presented as representative of the ACE/ATRIUM 11 uncertainty. However, in RAI-SNPB-28 the NRC staff questioned whether it would be more appropriate to represent the correlation

uncertainty with the [ ] statistics, given that it is more representative of the correlation's prediction capability. The RAI also asked for clarification on how the correlation uncertainties will be used in downstream Framatome methodologies.

Framatome's response to RAI-SNPB-26 discusses the second part of the question. The [ ] is the uncertainty that is applied in the MCPR safety limit methodology, described in ANP-10307PA, Revision 0, "AREVA MCPR Safety Limit Methodology for Boiling Water Reactors" (Reference 17). It is the NRC staff's understanding that this is the only CPR calculation that includes the correlation uncertainty.

The first part of the question is answered by portions of several of Framatome's RAI responses. [

]

As discussed in Framatome's response to RAI-SNPB-28, the [

]. Because of this, and because the data was seen to be relatively insensitive to the choice of correlating and validating data as discussed in Section 3.2.3.1.1 of this SE, "Identification of validation data," the NRC staff finds it acceptable to represent the overall correlation uncertainty with the uncertainty of the [ ]. However, this uncertainty must be adjusted to account for the increased uncertainty in the non-conservative subregions, as will be discussed next.

The equation used to determine the additive constant uncertainty (6.38 of the TR) comes from Reference 8 in the TR, which specifically notes that the pooling of variances assumes that the samples come from populations with the same underlying variance but different means. The reference suggests Bartlett's test for homogeneity of variance to determine whether this assumption holds for a set of data; the NRC staff performed this test on the ECPR data provided in the TR and found [

] Different peaking patterns are applied in different tests, and rods are limiting or potentially limiting only in certain tests; [

]. The tests that peaked each rod are presented in Figure 8.1 from the TR.

As discussed previously, non-conservative subregions were found to exist in [ ]. The NRC staff found it necessary to penalize [ ] to properly bound the uncertainty in these regions. [

]

Figure 3.4 – Tests by peaked rod positions, with positions that use non-conservatively predicted data highlighted.

[ ]

[ ]

In order to determine the magnitude of the [ ] that must be applied to [ ], the NRC staff first had to define one-sided 95/95 upper tolerance limits (UTLs) where the number of non-conservative predictions would be acceptable. This was done by incrementally increasing the limit from that of the overall dataset and checking the probability of the observed number of non-conservative points, using the same method as was originally used to identify the non-conservative subregions in Section 3.2.3.2.2, "Identification of non-conservative subregions." This process was repeated until the probability became acceptable (≥ 5 percent) for each of the three regions identified above. This resulted in upper tolerance limits [ ].

The uncertainties for the three regions were then developed by [ ]. This is consistent with how the uncertainties are applied in the safety limit calculation, [ ]. One-sided upper tolerance factors (*k*, per Owen (Reference 18), as discussed in Section 7.1.3 of the TR) were then calculated assuming the same number of data points as are in the regions that required the increased 95/95 limit. The standard deviation for the distribution was then calculated by subtracting 1 from the 95/95 upper tolerance limit and dividing by the *k*. [ ]. This information is summarized in Table 3.2 below.

Table 3.2 – Increased uncertainties for [ ].

[ ]

The [ ] provided in Table 3.2 shall be applied to [ ]. With these changes to make the correlation statistics more conservative, Goal 3.3.1 is satisfied.

<u>Transient Applications</u>

Section 7.3 of Reference 2 stated that [ ]. To ensure that the correlation's statistics were appropriately calculated, the NRC asked RAI-SNPB-20 to better understand the implications of this information.

[

]

The NRC staff also agrees, based on the RAI responses discussed in this section, that the application of a steady-state CPC to transients is conservative and that in particular the ACE/ATRIUM 11 behavior in transients is consistent with expectations and provides additional validation for the correlation.

3.2.4 Correlation Implementation

Over the course of the NRC staff's review of the ACE/ATRIUM 11 correlation it became apparent that an additional criterion was needed for the correlation's implementation in various codes and methodologies. Specifically, the NRC staff found that applicants should confirm that implementation in a code or method will not impact the predictive capability of the correlation and will appropriately capture the correlation's uncertainty.

In the initial submittal (Reference 2), Framatome provided analysis that used XCOBRA-T to predict the transient test results with the ACE/ATRIUM 11 correlation. This analysis demonstrated the use of the ACE/ATRIUM 11 within XCOBRA-T to appropriately predict boiling transition. Framatome also stated that the correlation is "designed for application to steady-state design analysis, core monitoring, Anticipated Operational Occurrences (AOO's), transient accidents, LOCA, and instability analysis for the ATRIUM 11 fuel design" and may also be applied in Framatome's co-resident fuel methodology.

However, Framatome did not discuss whether or not ACE/ATRIUM 11 would be applied in any codes other than XCOBRA-T. The NRC staff therefore asked RAI-SNPB-29 to obtain this additional information. Framatome's response stated that the ACE correlation is implemented in a code library called ACELIB, which is applied in XCOBRA, a steady-state core thermal-hydraulics code; XCOBRA-T, a transient core thermal-hydraulics code which was benchmarked against experiments in the TR; MICROBURN-B2, a 3D nodal core simulator code; SAFLIM-3D, Framatome's MCPR safety limit calculation code; RELAX, a LOCA code; and AURORA-B, a transient analysis code based largely around the SRELAP-5 system code. The use of a single library allows the implementation to be consistent across codes and eliminates a potential source of error.

As discussed in Section 3.2.3.1.1, "Identification of validation data," the ACE/ATRIUM 11 correlation was found to have a conservative bias for transient predictions using XCOBRA-T. The other transient code in which ACE/ATRIUM 11 is intended to be applied is AURORA-B, which was under review by the NRC staff at the same time as the ACE correlation. As discussed in Reference 10, the NRC staff requested that Framatome provide additional justification for using AURORA-B for ATRIUM 11 transient evaluations using the ACE/ATRIUM 11 correlation. This information was originally provided in Reference 9, and updated to correct errors and answer draft NRC RAIs in Reference 10.

For the XCOBRA-T transient analyses evaluated in the TR, [ ] needed to make ACE/ATRIUM 11 provide a conservative timing of dryout compared to the experiment was always substantially less than [ ]. However, the NRC staff found

that this was not necessarily the case for the AURORA-B transient analyses provided in Reference 10. Of the [ ] transient experiments that were not conservatively predicted using AURORA-B, [ ] fell outside of the [ ].

The NRC staff asked Framatome for additional justification of the adequacy of [ ] for use in AURORA-B, as documented in Draft RAI-A (reproduced in Reference 10).

Framatome stated in response that the stratified sampling methodology employed in the safety limit calculation adequately represents the entire additive constant uncertainty. In this methodology, a standard normal distribution is defined [ ]. These values are then applied as [ ] to perturb the uncertainty for the calculation of the MCPR safety limit. [ ]. Framatome stated in their RAI response that this means that sampling performed within this interval represents all values in the interval, [ ].

The NRC staff agrees that this system of sampling is appropriate for the purpose of determining the MCPR safety limit using in Framatome's methodology (Reference 17), where the quantity of interest is the number of rods in boiling transition at the 50 percent probability level with 95 percent confidence. The NRC staff cautions that this sampling system may not be adequate for analyses where extreme values are important. Though the methodology provides a good representation of the mean and standard deviation of the distribution as shown in Framatome's RAI response, it has the potential to underrepresent the tails of the distribution.

Considering that the sampling is expected to adequately represent the whole distribution (and not just those values lying within [ ], it is still important to confirm that AURORA-B presents an overall conservative bias, as would be expected of transient analyses using steady-state boiling transition correlations. Framatome argued in the second part of their response to Draft RAI-A that [ ] values would fall outside of [ ] standard deviations from the mean additive constant if the distribution were normally distributed with no bias, based on [ ] points drawn from a standard normal distribution. Because [ ] points had an additive constant uncertainty adjustment outside of these bounds, Framatome considers the correlation to provide a conservative prediction of the CP under transient conditions as simulated within AURORA-B. The NRC staff agrees that the evidence from CP testing supports the idea that ACE/ATRIUM 11 provides an overall conservatively-biased prediction of CP within the AURORA-B calculation framework.

The NRC staff also expressed a concern, however, that the use of ACE/ATRIUM 11 within different transient codes would introduce potential sources of uncertainty that would not be addressed by the safety limit calculation (which, as discussed above, is effectively the only calculation where CP uncertainties are captured). This RAI is documented as Draft RAI B in Reference 10. Framatome's response states that while there would be some difference expected between different transient analysis codes because of the use of different field equations and constitutive relations, this uncertainty is small overall and bounded by the conservative bias introduced by applying a steady-state code to transient conditions. While the

NRC staff believes this has been shown to be the case for the transient analysis codes discussed in this SE, it must be demonstrated for each new code that the ACE correlation will be used with. This will be discussed in Section 4.0, "Limitations and Conditions."

In conclusion, the NRC staff determined that the implementation of the ACE/ATRIUM 11 code has appropriate controls and that it has been shown to be conservative in transient applications within XCOBRA-T and AURORA-B. It is thus acceptable for use in these codes.

3.2.5 Other Considerations

Over the course of the review of the ACE/ATRIUM 11 correlation, the NRC staff became aware of a leaking fuel rod at the Kernkraftwerk Leibstadt (KKL) nuclear power plant in Switzerland, a BWR/6 operating on yearly cycles. The leaker was believed to have resulted from excessive cladding oxidation due to dryout. Subsequent inspections found widespread suspected occurrences of dryout in locations throughout the core. In the next cycle, steps were taken to increase the MCPR operating limit and prevent future instances of dryout. However, further inspections revealed even more suspected dryout indications after the compensatory measures were taken. Additional inspections found that dryout was believed to have occurred in several cycles before the leaking fuel rod was identified.

Dryout of the type observed at the plant was not observed in testing at similar bundle flow rates and powers. At no point during KKL's operation did the analytical methods developed by the fuel's vendor predict that margin to dryout would be sufficiently degraded for dryout to occur. In light of this operating experience suggesting sustained dryout during operation at steady state conditions, the NRC asked for additional information (Reference 11) on how Framatome provides reasonable assurance that adequate CP margin will be maintained during normal operation (including the effects of anticipated operational occurrences).

In response (Reference 12), Framatome provided a discussion of their overall process for calculating an operating limit MCPR (OLMCPR), which is based on NRC reviewed and approved calculational methodologies and empirical correlations derived from testing, all of which have passed stringent QA processes performed under Appendix B to 10 CFR Part 50. That Framatome's testing, correlations, codes, and methodologies have all been developed and validated under Appendix B programs and have received NRC review and approval does give confidence that the MCPR safety and operating limits would be adequately predicted to protect against dryout. On the other hand, these conditions were also true for the fuel that experienced dryout at KKL and they were apparently insufficient to help predict or prevent the occurrence of dryout.

However, Framatome's RAI response also indicated that they have specific operating and inspection experience that is directly relevant to the KKL dryouts. [

]

The NRC staff concluded that it is not appropriate to impose a generic limitation on the use of ATRIUM 11 fuel in response to the KKL dryouts. Though the exact set of phenomena that caused these dryouts are currently unknown, it is believed by the NRC staff that some power plants are more likely to be affected than others due to a number of factors, including power density, cycle length, fuel management strategy, and plant design. These factors, and others as appropriate, should be considered by Framatome and the NRC staff during a plant-specific implementation of the ATRIUM 11 fuel to determine if any further actions are warranted to ensure appropriate prediction of dryout margin. For example, post-irradiation inspection of ATRIUM 11 fuel following its insertion in BWRs with power densities similar to KKL may provide additional evidence that dryout margin can be adequately predicted in limiting circumstances.

4.0 LIMITATIONS AND CONDITIONS

The use of the ACE/ATRIUM 11 correlation is acceptable to the NRC staff for calculating the CPR for ATRIUM 11 fuel, subject to the following limitations and conditions:

1. The ACE/ATRIUM 11 correlation shall not be applied outside of the parameter ranges presented in Table 2.1 of ANP-10335P.

   Because the testing did not include flow in the internal water canister, the limits on mass flow rate are imposed on the mass flow rate in the heated section of the bundle (i.e., they do not include bypass flow that would be included if the bundle inlet mass flow rate were to be used). Also note that while Framatome did not specify [

   ].

   Additionally, the LPF limit of [ ] can be exceeded only for perturbed conditions in MCPR safety limit Monte Carlo calculations and for bundles that can be shown to be non-limiting (e.g., high burnup or controlled bundles).

2. For bundles with LPFs greater than [

   ].

   The following increased [ ] uncertainties shall be applied to the following listed rod positions [ ]:

[

]

3. Application of the ACE/ATRIUM 11 correlation in a transient analysis methodology requires verification that the correlation conservatively predicts CP compared to test data and demonstrates similar behavior compared to other implementations of the correlation. Framatome shall not apply the ACE/ATRIUM 11 correlation in transient analysis methodologies other than XCOBRA-T and AURORA-B without first verifying the appropriate correlation behavior and conservatism.

5.0 CONCLUSIONS

The NRC staff reviewed ACE/ATRIUM 11 CPC, as documented in ANP-10335P, and determined that it is acceptable for use in steady-state and transient CP calculations for ATRIUM 11 fuel, subject to the limitations and conditions discussed above in Section 4.0. This correlation therefore provides an adequate basis for protection against the SAFDL prohibiting boiling transition in 99.9 percent of fuel rods at steady state and transient conditions and, consequently, for calculation of BWR safety and operating limits for plant technical specifications.

6.0 REVIEW FRAMEWORK

GOAL	**The critical heat flux or critical power correlation must be acceptable for use in reactor safety licensing calculations (i.e., the correlation must be able to be trusted).**
G1	The experimental data must be accurate.
G1.1	The test facility must be demonstrated to be credible.
G1.1.1	The test facility should be described in appropriate detail and references should be provided. At a minimum, this should include a loop description, test section description, and heater rod description. A reference to any applicable documents which describe the test facility should be provided.
G1.1.2	The test procedures should be described in appropriate detail and references should be provided. This should be provided for both steady-state and transient tests. A reference to any applicable documents which describe the testing procedures should be provided.
G1.1.3	The results of the test facility should be demonstrated to be accurate compared to an external source.
G1.2	The local conditions in the reactor fuel bundle must be reproduced in the test bundle.
G1.2.1	The ranges of the experimental parameters (e.g., pressure, powers, flow rates) should be representative of the values expected in a reactor during normal operation and AOOs. This includes radial power peaking in BWR tests.
G1.2.2	The grid spacers and heater rods used in the test bundle should result in the same flow field as those used in the reactor fuel bundle. At a minimum, this includes grid spacer design and axial

	location, rod diameter, and heated length. Typically, the grid spacers and heated rods used in the test bundle should be within the manufacturing tolerances of the grid spacers and fuel rods used in the fuel bundle in the reactor.
G1.2.3	Any differences between the test bundle and the reactor bundle should be addressed. This includes components which are not in the reactor bundle but are needed for testing purposes.
G1.2.4	The local powers in the test bundle should reflect the expected local powers in the reactor assembly/bundle. This is accomplished through testing of representative axial and radial power shapes.
G1.2.5	Any part length or unheated rods in a reactor bundle should be accurately reflected in the test bundle. Additionally, any part length rods should have the same heated length in both the reactor and test bundles.
G1.3	The experiment must provide accurate measurements of all important parameters including CHF or CP.
G1.3.1	The measurement uncertainties of all measured parameters and other variables important to the CHF or CPC should be reasonably low.
G1.3.2	Important experimental parameters (e.g., pressure, flow, temperature, and power) should have diverse and redundant means of experimentally measuring their values.
G1.3.3	The instrumentation should be repeatedly calibrated and checked to ensure accurate measurements.
G1.3.4	The method for determining DNB or dryout should ensure an accurate capture of the CHF or CP. This method includes the testing procedures used to take a single data point and the criteria used to determine that DNB or dryout has occurred. This includes the stability conditions and the procedure for approaching DNB or dryout. This should be provided for both steady-state and transient tests as the tests often have different testing procedures and may have different criteria for determining whether a critical boiling transition has occurred.
G1.3.5	The CHF or CP experimental uncertainty should be quantified by determining the variance of the CHF or CP measurement through test repetition. This error should be small when compared with the uncertainty in the correlation.
G1.3.6	Heat losses from the test bundle should be well characterized.
G2	The correlation must be generated in a logical fashion.
G2.1	The mathematical form of the correlation must be appropriate.
G2.1.1	The mathematical form of the model contains all necessary variables.

G2.1.2	The reasoning behind the mathematical form of the correlation should be discussed.
G2.2	The process for determining the correlation's coefficients must be appropriate.
G2.2.1	The training data (i.e., the data used to generate the coefficients of the correlation) should be identified.
G2.2.2	The method for calculating the correlation's coefficients should be described.
G2.2.3	The method for calculating the R or K factors and the additive constants (for both full length and part length rods) should be described. Further, a description should be provided of how such values are calculated if dryout is not measured on the rod under consideration (CP only).
G3	The correlation must have sufficient validation as demonstrated by appropriate quantification of its uncertainty.
G3.1	The validation data must be appropriately distributed throughout the expected domain.
G3.1.1	The validation data (i.e., the data used to quantify the correlation's error) should be identified and should be separate from the training data.
G3.1.2	The computational domain of the correlation should be mathematically defined.
G3.1.3	It should be ensured that the correlation will not be used outside of the computational domain.
G3.1.4	The expected domain of the correlation should be appropriately defined and justified. At a minimum, the input variables should be compared two at a time using a 2-D plot with input variable 1 on the x-axis and input variable 2 on the y-axis. Each plot should display the validation data, as well as expected domain for that variable combination and some justification of that expected domain. Any anticipated new regions of application should be discussed.
G3.1.5	Empty regions of the expected domain should be justified to be unconditionally conservative.
G3.1.6	The data should be well distributed throughout the expected domain with a sufficient density.
G3.1.7	Ideally, the experimental input conditions would be randomized during each run, but this is impractical due to testing considerations. Therefore, some method of ensuring that the experimental data taken is independent of any bias due to similar input conditions should be demonstrated. Further, input conditions which can be randomized should be.

G3.2		Any inconsistencies in the validation error must be accounted for appropriately.
	G3.2.1	The validation error should be investigated to determine if it contains any sub-groups which are obviously not from the same population (i.e., not poolable).
	G3.2.2	The expected domain should be investigated to determine if contains any non-conservative subregions.
G3.3		The correlation statistics must be conservatively calculated.
	G3.3.1	The calculation of the correlation statistics should reflect any changes deemed necessary to generate a conservative correlation statistic.
G4		The correlation must be correctly implemented.

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15. USNRC, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," NUREG-0800, Section 4.4, "Thermal and Hydraulic Design," Revision 2, March 2007, ADAMS Accession No. ML070550060 (Publicly Available).

16. Kaizer, J. S., 2015, "Identification of Nonconservative Subregions in Empirical Models Demonstrated Using Critical Heat Flux Models," Nuclear Technology, 190:65–71, 2015.

17. AREVA, "AREVA MCPR Safety Limit Methodology for Boiling Water Reactors," ANP-10307PA, Revision 0, June 2011, ADAMS Accession No. ML11259A022 (Non-Publicly Available)/ML11259A021 (Publicly Available).

18. Owen, D .B., "Factors for One-Sided Tolerance Limits and for Variables Sampling Plans," Sandia Corporation Report SCR-607, March 1963, ADAMS Accession No. ML14031A495 (Publicly Available).

Principal Contributor: Reed Anzalone, NRR/DSS/SNPB

Date: May 25, 2018

RESOLUTION OF COMMENTS BY THE OFFICE OF NUCLEAR REACTOR REGULATION
ON DRAFT SAFETY EVALUATION FOR TOPICAL REPORT ANP-10335P, REVISION 0,
"ACE/ATRIUM 11 CRITICAL POWER CORRELATION"

FRAMATOME, INC.

PROJECT NO. 728/DOCKET NO. 99902041

This attachment provides the U.S. Nuclear Regulatory Commission (NRC) staff's review and disposition of the comments made by Framatome Inc. (formerly AREVA Inc.) on the draft safety evaluation (SE) for Topical Report ANP-10335P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation."

Page*	Line(s)*	Proposed Change	NRC Resolution of Comment
1	5	Page 1, line 5. Typo: Change "CPR" to "CPC"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
2	34	Change "Reference 134" to "Reference 14"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
3	29	Change "Chapter 7" to "Chapter 6"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
3	36	Change "Chapter 7" to "Chapter 6"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
4	13	Change "indirectly" to "directly"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
4	15	Change "indirectly" to "directly"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
6	33	Change " " to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
6	33	Change " " to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.

Page*	Line(s)*	Proposed Change	NRC Resolution of Comment
6	35-36	Change " " to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
6	37	Change " " to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
6	40	Change "[a mechanistic correlation]" to "a mechanistic correlation"	The NRC staff agrees that the information is non-proprietary. The information was marked accordingly in the final SE.
7	46-47	Delete "...through test data taken in the ATRIUM-10 test campaign,"	The NRC staff agrees with the proposed change. The text was deleted in the final SE.
8	9	Change " " to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
8	28-29	Change "and position the bundle in the center of the channel" to "[and position the bundle in the center of the channel]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
9	21-25	Change " " to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.

Page*	Line(s)*	Proposed Change	NRC Resolution of Comment
9	27	Change "a wide a wide" to "a wide"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
9	37	Change " [ ] " to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
10	11-12	Change "[ ] ." to "[ ]."	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
10	22	Change "[ ] " to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
10	25-26	Change "[ ] ." to "[ ]."	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
11	12	Change "the though" to "though the"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
11	12	Change "[ ] " to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
11	23-24	Change " [ ]" to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
14	17-18	Change " ." to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
17	42-43	Change " " to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.

Page*	Line(s)*	Proposed Change	NRC Resolution of Comment
18	1	Change " " to "[...]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
18	2	Change " [ ] , [" to "[...]	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
19	27	Change "or because the enthalpy of the film reaches that of the bulk flow" to "or because the annular film enthalpy reaches that of saturated vapor"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
19	31	Change "[a mechanistic treatment of boiling transition]" to "a mechanistic treatment of boiling transition"	The NRC staff agrees that the information is non-proprietary. The information was marked accordingly in the final SE.
20	17	Change "the both the" to "both the"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
20	35	Change " " to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
20	35-39	Delete "However, as will be discussed in Section 3.2.3.2.1, "Calculation of correlation statistics," Framatome's response to RAI-SNPB-28 stated that it was necessary to [ ]. It is therefore incorrect to state that some data is reserved exclusively for validation."	The text was modified in the final SE to clarify the NRC position. The information was not deleted but reworded to correct inaccuracies in the draft SE.
21	12	Change "RAI-SNPB-15" to "RAI-SNPB-16"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
21	33	Change "how such these values" to "how these values"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
22	1	Change "In the Reference 2" to "In Reference 2"	The NRC staff agrees with the proposed change. The error was corrected in the final SE.

Page*	Line(s)*	Proposed Change	NRC Resolution of Comment
24	23-28	Delete 'As was discussed in Section 3.2.2.2.1 of this SE, "Identification of training data," it was revealed that though the data was partitioned into correlating and validating datasets for the purposes of fitting the linear and nonlinear coefficients, [ ]. It is therefore incorrect to state that some data was reserved for validation purposes. This will be discussed in additional detail in Section 3.2.3.3.1, "Calculation of correlation statistics."'	The text was modified in the final SE to clarify the NRC position. The information was not deleted but reworded to correct inaccuracies in the draft SE.
24	30	Delete "However, despite the fact that [ ]"	The NRC staff agrees with the proposed change. The text was deleted in the final SE.
25	15-16	Delete the text "that the data was not fully partitioned into correlating and validating datasets, given"	The text was modified in the final SE to clarify the NRC position. The information was not deleted but reworded to correct inaccuracies in the draft SE.
25	22	Change " " to "[ ]"	The text was modified in the final SE to clarify the NRC position. The information was not deleted but reworded to correct inaccuracies in the draft SE.
26	19	Change " [ ]" to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
35	28-29	Change "partitioned into correlating and validating datasets for the purposes of [ ]." to "partitioned and the validating dataset can be used exclusively to [ ]."	The NRC staff agrees with the proposed change. The error was corrected in the final SE.
38	28	Change " ," to " ...]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
38	30	Change "argued that [even before " to "argued that even before "	The NRC staff agrees that the information is non-proprietary. The information was marked accordingly in the final SE.

Page*	Line(s)*	Proposed Change	NRC Resolution of Comment
38	36	Change "prediction of dryout.]" to "prediction of dryout."	The NRC staff agrees that the information is non-proprietary. The information was marked accordingly in the final SE.
38	39	Change "that [the existing" to "that the existing".	The NRC staff agrees that the information is non-proprietary. The information was marked accordingly in the final SE.
38	43	Change " ... " to "...]".	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
39	1	Change " " to "[".	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
40	11-14	Change "defined [ ]" to "defined [ ]".	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
42	30-31	Change "specify [" to "specify [ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
42	39	Change "than , [..." to "than [..."	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.
42	42	Change " " to "[ ]"	The NRC staff agrees that the information is proprietary. The information was marked accordingly in the final SE.

AREVA

February 27, 2015
NRC:15:012

U.S. Nuclear Regulatory Commission
Document Control Desk
11555 Rockville Pike
Rockville, MD 20852

Request for Review and Approval of ANP-10335P Revision 0, "ACE/ATRIUM 11 Critical Power Correlation"

Ref. 1: ANP-10249P-A Revision 2, "ACE/ATRIUM-10 Critical Power Correlation," AREVA, March 2014.

Ref. 2: ANP-10298P-A Revision 1, "ACE/ATRIUM 10XM Critical Power Correlation," AREVA, March 2014.

AREVA Inc. (AREVA) requests the NRC's review and approval of the topical report ANP-10335P Revision 0, "ACE/ATRIUM 11 Critical Power Correlation" dated February 2015, for referencing in licensing actions.

This report presents the development of and justification for using the ACE/ATRIUM 11 Critical Power Correlation to predict critical power for the new ATRIUM 11 fuel design. The ACE correlation form has been applied for two current NRC licensed critical power correlations, ACE/ATRIUM 10 and ACE/ATRIUM 10XM (References 1 and 2). The same correlation form is applied, unchanged, for the ACE/ATRIUM 11 critical power correlation.

As a point of note, the NRC sent a Staff Member to Karlstein, Germany in January of 2014 to audit the KATHY test facility and observe ATRIUM 11 testing, which is utilized in the correlation development presented in this Topical Report (TR). The NRC audit and familiarization of the NRC Staff Member with the KATHY test facility was intended to aid in the efficiency of the review of this TR.

This TR is needed to support reloads of the new ATRIUM 11 fuel design in early 2019. AREVA anticipates the need for a Safety Evaluation for this TR in early 2016. This would allow for a 2 year review of LARs that will support introduction of ATRIUM 11 fuel. AREVA is currently engaged in lead test assembly programs for the ATRIUM 11 fuel design and there is commercial interest in taking advantage of the safety and performance improvements of the ATRIUM 11 fuel design as noted below. AREVA anticipates that there will be Licensees interested in implementing reload quantities of ATRIUM 11 fuel by the 2019 target date.

As part of Industry's and AREVA's goals of improving thermal margins and fuel reliability, AREVA is introducing the ATRIUM 11 BWR fuel design to the U.S. market. The ATRIUM 11 design incorporates features that improve many key aspects of the fuel; among them are thermal margins, cold shutdown margins, stability, resistance to distortion and resistance to debris. The introduction of ATRIUM 11 is important to achieve lower fuel rod duty and to increase safety margins. A critical item needed to

AREVA INC.

3315 Old Forest Road, Lynchburg, VA 24501
Tel.: 434 832 3000 - www.areva.com

support the evolution to ATRIUM 11 fuel is the critical power correlation applicable to the design. This correlation is key to the design, application and monitoring of the fuel and is one of items needed early in the design cycle of the fuel.

AREVA considers some of the material contained in the enclosed documents 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 report are found in Enclosures 3 and 4, respectively. Enclosure 2 is the notarized Affidavit.

In support of the Office of Nuclear Reactor Regulation's prioritization efforts, the TR Prioritization Scheme is included as Enclosure 1 of this letter.

There are no commitments contained within the enclosures to this letter.

If you have any questions related to this information, please contact Mr. Alan Meginnis by telephone at (509) 375-8266, or by e-mail at Alan.Meginnis@areva.com.

Sincerely,

Pedro Salas, Director
Licensing & Regulatory Affairs
AREVA Inc.

Enclosures:

1. TR Prioritization Scheme
2. Notarized Affidavit
3. Proprietary Version of ANP-10335P Revision 0, "ACE/ATRIUM 11 Critical Power Correlation"
4. Non-Proprietary Version of ANP-10335NP Revision 0, "ACE/ATRIUM 11 Critical Power Correlation"

cc: J. G. Rowley
Project 728

TR Prioritization Scheme			
Title: ANP-10335P Revision 0, "ACE/ATRIUM 11 Critical Power Correlation"			
Expect submitting FY	**TAC**	**PM**	**Today's Date:**
Technical Review Division(s)		**Technical Review Branch(s)**	
Factors	**Select the Criteria That the TR satisfies**	**Points can be Assigned for Each Criteria**	**Assigned Points**
TR Classification (Select one only)	Resolve Generic Safety Issue (GSI)	6	2
	Emergent NRC Technical Issue	3	
	New technology improves safety	2	
	TR Revision reflecting current requirements or analytical methods.	2	
	Standard TR	1	
TR Applicability (Select one only)	Potential industry-wide applications	3	2
	Potentially applicable to entire groups of licensees.	2	
	Intended for only partial groups of licensees.	1	
TR Implementation Certainty (Select one only)	Industry-wide Implementation expected	3	0
	Expected implementation by an entire group of licensees (BWROG, PWROG, BWRVIP, etc.) who sponsored the TR.	2	
	Docketed intent by U.S. plant(s) but no formal LAR schedule yet	1	
	No US plants have indicated strong intent on docket to implement yet.	0	
Tie to a LAR (Select if applicable)	A SE is requested by a certain date (less than two years) to support a licensing activity or renewal date (note it in Comments)	3	0
Review Progress (Points are cumulative as applicable)	Accepted for review	0.3	
	RAI issued	0.5	
	RAI responded	1.2	
	SE Drafted	2.0	
Management (LT/ET) discretion adjustment		-3 to +3	
Total Points (Add the total points from each factor and total here):			

Comments: As part of Industry's and AREVA's goals of improving thermal margins and fuel reliability, AREVA is introducing the ATRIUM 11 BWR fuel design to the US market. The ATRIUM 11 design incorporates features that improve many key aspects of the fuel; among them are thermal margins, cold shutdown margins, stability, resistance to distortion and resistance to debris. The introduction of ATRIUM 11 is important to achieve lower fuel rod duty and to increase safety margins. A critical item needed to support the evolution to ATRIUM 11 fuel is the critical power correlation applicable to the design. This correlation is key to the design, application and monitoring of the fuel and is one of items needed early in the design cycle of the fuel.

AFFIDAVIT

STATE OF WASHINGTON)
) ss.
COUNTY OF BENTON)

1. My name is Alan B. Meginnis. I am Manager, Product Licensing, for AREVA Inc. and as such I am authorized to execute this Affidavit.

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

3. I am familiar with the AREVA information contained in the report ANP-10335P Revision 0, "ACE/ATRIUM 11 Critical Power Correlation," dated February 2015 and referred to herein as "Document." Information contained in this Document has been classified by AREVA as proprietary in accordance with the policies established by AREVA for the control and protection of proprietary and confidential information.

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

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

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

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

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

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

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

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

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

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

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

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

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

[signature]

SUBSCRIBED before me this 17th day of February, 2015.

[signature]

Susan K. McCoy
NOTARY PUBLIC, STATE OF WASHINGTON
MY COMMISSION EXPIRES: 1/14/2016

SUSAN K. MCCOY NOTARY PUBLIC STATE OF WASHINGTON COMMISSION EXPIRES 01-14-16

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

May 8, 2015

Mr. Pedro Salas, Director
Licensing and Regulatory Affairs
AREVA Inc.
3315 Old Forest Road
Lynchburg, VA 24501

SUBJECT: ACCEPTANCE FOR REVIEW OF AREVA INC. TOPICAL REPORT ANP-10335P, REVISION 0, "ACE/ATRIUM 11 CRITICAL POWER CORRELATION" (TAC NO. MF5841)

Dear Mr. Salas:

By letter dated February 27, 2015 (Agencywide Documents Access and Management System Accession Number ML15062A553), AREVA Inc. (AREVA) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review Topical Report (TR) ANP-10335P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation." The NRC staff has performed an acceptance review of TR ANP-10335P, Revision 0. We have found that the material presented is sufficient to begin our comprehensive review. The NRC staff expects to issue its request for additional information by January 8, 2016, and issue its draft safety evaluation (SE) by August 26, 2016. This schedule takes into consideration the NRC's current review priorities and available technical resources and may be subject to change. If modifications to these dates are deemed necessary, we will provide appropriate updates to this information.

The NRC staff estimates that the review will require approximately 840 staff hours including project management time. The review schedule milestones and estimated review costs were discussed and agreed upon in a telephone conference between AREVA Product Licensing Manager, Alan Meginnis, and the NRC staff on April 16, 2015.

Section 170.21 of Title 10 of the *Code of Federal Regulations* requires that TRs are subject to fees based on the full cost of the review. You did not request a fee waiver; therefore, NRC staff hours will be billed accordingly.

As with all TRs, the SE will be reviewed by the NRC's Office of the General Counsel (OGC) to determine whether it falls within the scope of the Congressional Review Act (CRA). During the course of this review, OGC considers whether any endorsement or acceptance of a TR by the NRC amounts to a rule as defined in the CRA. If this initial review concludes that the SE, with its accompanying TR, may be a rule, the NRC will forward the package to the Office of Management and Budget (OMB) for further review and consideration. Any review by OMB would impact the schedule for the issuance of the final SE.

If you have questions regarding this matter, please contact me at (301) 415-4053.

Sincerely,

Jonathan G. Rowley, Project Manager
Licensing Processes Branch
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 728

cc: See next page

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

April 11, 2016

Mr. Gary Peters, Director
Licensing and Regulatory Affairs
AREVA Inc.
3315 Old Forest Road
Lynchburg, VA 24501

SUBJECT: REQUEST FOR ADDITIONAL INFORMATION RE: AREVA INC. TOPICAL REPORT ANP-10335P/NP, "ACE/ATRIUM 11 CRITICAL POWER CORRELATION" (TAC NO. MF5841)

Dear Mr. Peters:

By letter dated February 27, 2015 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML15062A553), AREVA INC. (AREVA) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review and approval Topical Report ANP-10335P/NP, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation." Upon review of the information provided, the NRC staff has determined that additional information is needed to complete the review. On March 15, 2016, Alan Meginnis, AREVA Product Licensing Manager, and I agreed that the NRC staff will receive the response to the enclosed RAI questions within 120 days from the date of this letter.

If you have any questions regarding the enclosed RAI questions, please contact me at 301-415-4053.

Sincerely,

Jonathan G. Rowley, Project Manager
Licensing Processes Branch
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 728

Enclosure:
RAI Questions

REQUEST FOR ADDITIONAL INFORMATION

RELATED TO AREVA INC

TOPICAL REPORT ANP-10335P/NP

"ACE/ATRIUM 11 CRITICAL POWER CORRELATION"

RAI-SNPB-1

Please provide references to documents describing the test loop and facility in greater detail, as well as the quality assurance program to be applied.

RAI-SNPB-2

Please provide a description of benchmarks performed with KATHY against other testing facilities, as well as a reference to documents where these benchmarks are described in detail.

RAI-SNPB-3

Only [ ] were tested in the development of the ACE/ATRIUM 11 correlation. Please provide a justification for not testing [ ].

RAI-SNPB-4

Please discuss the range of tested transient conditions, specifically including a discussion of [ ].

RAI-SNPB-5

Please provide additional justification for the use of [ ] up to [ ] when the highest tested [ ] is [ ].

RAI-SNPB-6:

Please provide additional details on the method used to develop [uncertainty discussed on]. Any response should discuss [ ].

RAI-SNPB-7:

As discussed in Section 9.0 of ANP-10335P, the [ ] in the test assembly is different from that of the production assembly. Please provide additional justification for why a correlation developed with this difference in the test assembly would be

applicable to a production assembly. Any justification should specifically address the parameters that could be affected by such a difference and the approximate magnitude of the impact.

RAI-SNPB-8:

Please provide a brief discussion of the procedures for measuring steady-state and transient critical power data points. Also provide references to documents discussing the critical power test procedures in further detail, including the conditions required to ensure stability and the criterion for determining that dryout has occurred.

RAI-SNPB-9:

Please provide additional information about the design of the ACE/ATRIUM 11 critical power tests, including a discussion of how bias was eliminated from the testing program. Page 7-9 of ANP-10335P referenced full map, partial map, and statistical design of experiments tests – please define each of these terms and discuss how the experimental design differs between them. Also, please include a reference for a document discussing procedures for design of experiments for the KATHY loop.

RAI-SNPB-10:

Please provide the values of measurement uncertainties in the KATHY loop, with a focus on the uncertainties in the parameters discussed in Section 6.13 of ANP-10335P. Please also provide a brief discussion of how each value was derived.

RAI-SNPB-11:

Please provide a discussion of the instrumentation provided in the KATHY loop. The information provided should include a brief discussion of how diversity and redundancy of key measurements are ensured.

RAI-SNPB-12:

Please briefly describe the calibration of the instruments at the KATHY facility, including the frequencies of instrument calibration and reasons for those frequencies. Please also include a reference to a document describing the calibration in detail.

RAI-SNPB-13:

Please discuss the uncertainties associated with measurement of critical power in both steady-state and transient testing. Any response should include a quantification of the measurement uncertainty and a description of how the value was obtained.

RAI-SNPB-14:

Please discuss the heat losses from the test section, including how these losses vary depending on key parameters (test section power, flow rate, etc.).

RAI-SNPB-15:

It is not clear how the [ ] boundary conditions for the ACE/ATRIUM 11 correlation were chosen. Please explain the [ ] boundary conditions for the ACE/ATRIUM 11 correlation in further detail, especially including the [ ] discussed in ANP-10335P Section 6.7.

RAI-SNPB-16:

Please provide a discussion of the process used to fit the coefficients detailed in Section 6 of ANP-10335P. Since it is the NRC staff's understanding that [ ], the response should include a discussion of [ ]. The response could be a reference to an existing document.

RAI-SNPB-17:

What is the criterion for determining [ ] in the second-to-last paragraph of Page 6-22 in ANP-10335P?

RAI-SNPB-18:

What was the purpose of the [ ]? What is ["uncertainty in the value of the mean additive constant," referenced on Page 6-25 of], and how is it defined?

RAI-SNPB-19:

What is the basis for selecting [ ] of the data for correlation and [ ] for validation? How does [ ] impact the correlation uncertainty? The response should address both the experimental critical power ratio (ECPR) uncertainty and the additive constant uncertainty.

RAI-SNPB-20:

Please discuss in additional detail why it is considered appropriate [ ]. Were [ ] discussed in Section 7.3 applied to the correlation during the uncertainty assessment?

RAI-SNPB-21:

The topical report states in Section 6.13.1 that there is no lower limit on [ ]. Does AREVA plan to use the ACE/ATRIUM 11 correlation [ ]? If so, please provide additional justification.

RAI-SNPB-22:

Does AREVA plan to use the ACE/ATRIUM 11 correlation at [ ] greater than [ ]? If so, will some kind of upper limit on [ ] actually be applied?

RAI-SNPB-23:

Please clarify when the [ ] will be applied.

RAI-SNPB-24:

Please provide plots of the computational domain. These plots should use pairs of the key parameters ([ ]) for the x-axes and y-axes. Separate versions of the plots should be included for the correlation and validation data, as well as the combined dataset. Each plot should also include lines denoting the computational range of each parameter.

For each obvious region that lacks experimental data (especially validation data) lying within the computational domain, please justify why it is not possible to enter this region in an operating reactor. Alternatively, justify the correlation's behavior in the region.

RAI-SNPB-25:

Please provide additional explanation and justification of the trend of increasing ECPR standard deviation as a function of pressure. It is unclear to the NRC staff why this increasing variability should result from [ ], as discussed in Section 7.1.3 of ANP-10335P.

RAI-SNPB-26:

Please justify why the [ ] is considered poolable, considering that the mean and standard deviation of the ECPR vary significantly between [ ]. Please also discuss why the [ ] provided in [ ] do not appear to appropriately match the data.

RAI-SNPB-27:

There appears to be a non-conservative subregion between [ ] on Figures 7.1 and 7.9. There is another potentially nonconservative region at [ ]. Please justify why it is acceptable to use the correlation in these areas. Any discussion should address how the correlation uncertainties presented in the topical report account for the uncertainty in these areas.

RAI-SNPB-28:

Please provide additional justification for why it is appropriate to represent the ACE/ATRIUM 11 uncertainty with the ECPR distribution determined from the [ ] rather than the [ ]. The response should discuss how the correlation uncertainties will be applied in other methodologies.

RAI-SNPB-29:

Will ACE/ATRIUM 11 be implemented in codes other than XCOBRA-T? If so, please discuss how it will be implemented and provide the criteria that will be used to demonstrate that the implementation was appropriate.

RAI-SNPB-30:

Figures 2.1, 7.1, and 7.9 use units of kW. Were these intended to be MW?

framatome

January 26, 2018
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U.S. Nuclear Regulatory Commission
Document Control Desk
11555 Rockville Pike
Rockville, MD 20852

Revision to a Response to Request for Information Regarding AREVA Inc. Topical Report ANP-10335P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation"

Ref. 1: Letter, Pedro Salas (AREVA) to Document Control Desk (NRC), "Request for Review and Approval of ANP-10335P Revision 0, 'ACE/ATRIUM 11 Critical Power Correlation'," NRC:15:012, February 27, 2015.

Ref. 2: Letter, Gary Peters (AREVA) to Jonathan Rowley (NRC), "Response to a Request for Additional Information Regarding Topical Report ANP-10335P, Revision 0, 'ACE/ATRIUM 11 Critical Power Correlation'," NRC:16:020, August 11, 2016.

Framatome Inc. (Framatome, formerly AREVA Inc.) requested the NRC review and approval of Topical Report (TR) ANP-10335P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation" in Reference 1. The NRC provided a request for additional information (RAI), and Framatome responded to the RAI in Reference 2. As discussed via telephone, Framatome is providing a revision to that response, enclosed with this letter. Please note that only the response to question 14 of the RAI response was revised. For convenience, the complete RAI response with revision is enclosed. Revision 1 of ANP-10335Q1P will be the only version of the RAI response document which will be included in the final PA version of the Topical Report.

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

There are no commitments within this letter or its enclosures.

If you have any questions related to this information, please contact Mr. Morris E. Byram by telephone at (509) 375-8166, or by e-mail at Morris.Byram@areva.com.

Sincerely,

Gary Peters

Gary Peters, Director
Licensing & Regulatory Affairs
Framatome, Inc.

cc: J. G. Rowley
Project 728

Enclosures:

1. Proprietary copy of ANP-10335Q1P, Revision 1, "ACE/ATRIUM 11 Critical Power Correlation - RAIs"

2. Non-Proprietary copy of ANP-10335Q1NP, Revision 1, "ACE/ATRIUM 11 Critical Power Correlation - RAIs"

3. Notarized Affidavit

AFFIDAVIT

STATE OF WASHINGTON)
) ss.
COUNTY OF BENTON)

1. My name is Morris Byram. I am Manager, Product Licensing, for Framatome Inc. (Framatome) and as such I am authorized to execute this Affidavit.

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

3. I am familiar with the Framatome information contained in the report ANP-10335Q1P, Revision 1, entitled "ACE/ATRIUM 11 Critical Power Correlation - RAIs" referred to herein as "Document." Information contained in this document has been classified by Framatome as proprietary in accordance with the policies established by Framatome for the control and protection of proprietary and confidential information.

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

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

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

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

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

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

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

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

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

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

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

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

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

[signature]

SUBSCRIBED before me this 25 day of January, 2018.

[signature]

SUSAN K MCCOY
NOTARY PUBLIC - WASHINGTON
COMMISSION EXPIRES 01-14-2020

0414-12-F04 (Rev. 001, 03/10/2016)

AREVA

ACE/ATRIUM 11 Critical Power Correlation - RAIs

ANP-10335Q1NP
Revision 1

Topical Report

January 2018

AREVA Inc.

Nature of Changes

Item	Section(s) or Page(s)	Description and Justification
1	Page 50	Revised RAI #14.

Contents

List of Tables

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Nomenclature

Acronym	Definition
ASCII	American Standard Code for Information Interchange
BT	Boiling Transition
BWR	Boiling Water Reactor
CFR	Code of Federal Regulations
CHF	Critical Heat Flux
CP	Critical Power
CPR	Critical Power Ration, defined to be the assembly critical power divided by the assembly operation power
DC	Direct Current
ECPR	Experimental Critical Power Ratio, defined as the calculated critical power divided by the measured critical power
LPF	Local Peaking Factor
MCPR	Minimum CPR of all assemblies in the reactor core
NIST	National Institute of Standards and Technology
PWR	Pressurized Water Reactor
RAI	Request for Additional Information
SDE	Statistical Design of Experiments

1.0 INTRODUCTION

A boiling water reactor ACE/ATRIUM™* 11 critical power correlation topical report is provided in Reference 2. This document provides responses to a Request for Additional Information (RAI) (Reference 1) on that topical report.

* ATRIUM is a trademark of AREVA Inc.

Question 1:

Please provide references to documents describing the test loop and facility in greater detail, as well as the quality assurance program to be applied.

Response 1:

All of the data for the ACE/ATRIUM 11 critical power correlation were taken at the AREVA KATHY thermal-hydraulic test loop located in Karlstein, Germany. Figure 1 shows that the thermal hydraulic test facility is a high pressure water heat transfer loop containing a test vessel (shown in Figure 2) with the test assembly and upper and lower bus bars, high pressure coolers, a direct contact condenser, an electrically heated pressurizer, and the main circulation pumps. Two inlet flow lines of different sizes are shown. The different sizes allow fine control of the flow rate over a broad range. The test loop is rated at [ ] The DC power supply consists of four thyristor controlled rectifiers, providing a total electrical current of
[ ]

The data acquisition system samples the analog signals of the loop instrumentation, digitizing them with 16 bit analog to digital converters and stores the signals on hard disk. The hardware of the data acquisition system is based on National Instruments SCXI-bus components (Reference 32). [

] Six PC's are used: one controls the acquisition and data flow, three provide display and visualization of selected channels including thermocouples during CHF tests. One computer is used to display test results following each test run and one computer is used by the test monitoring engineer to access results directly. The data acquisition software is based on the programming language of "LabView". Evaluation software is applied to transfer the raw data (voltage) into physical values (pressure, temperature, etc.) is written in "C".

Key instrumentation in the KATHY loop is described in the response to RAI question 11.

Test loop uncertainties are given as part of the response to RAI questions 10 and 13.

A general description of the KATHY loop with additional details is available in
[ ] The quality assurance program applied to the testing is provided in
[ ] The quality assurance program is periodically audited by the AREVA U.S. Fuel group to ensure that the testing work performed under it satisfactorily meets the requirements of 10 CFR 50 Appendix B.

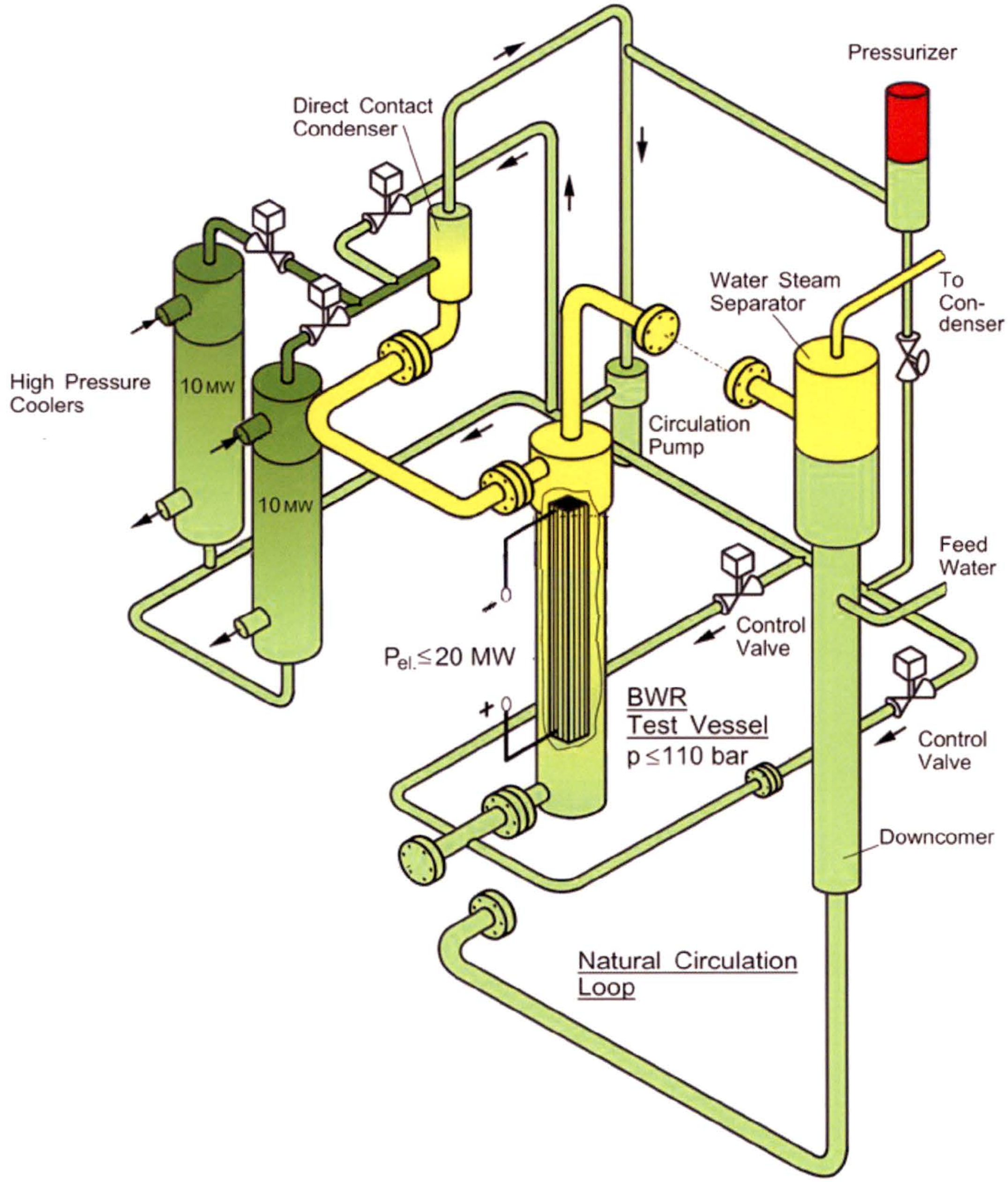

Figure 1. KATHY Thermal-hydraulic Test Loop

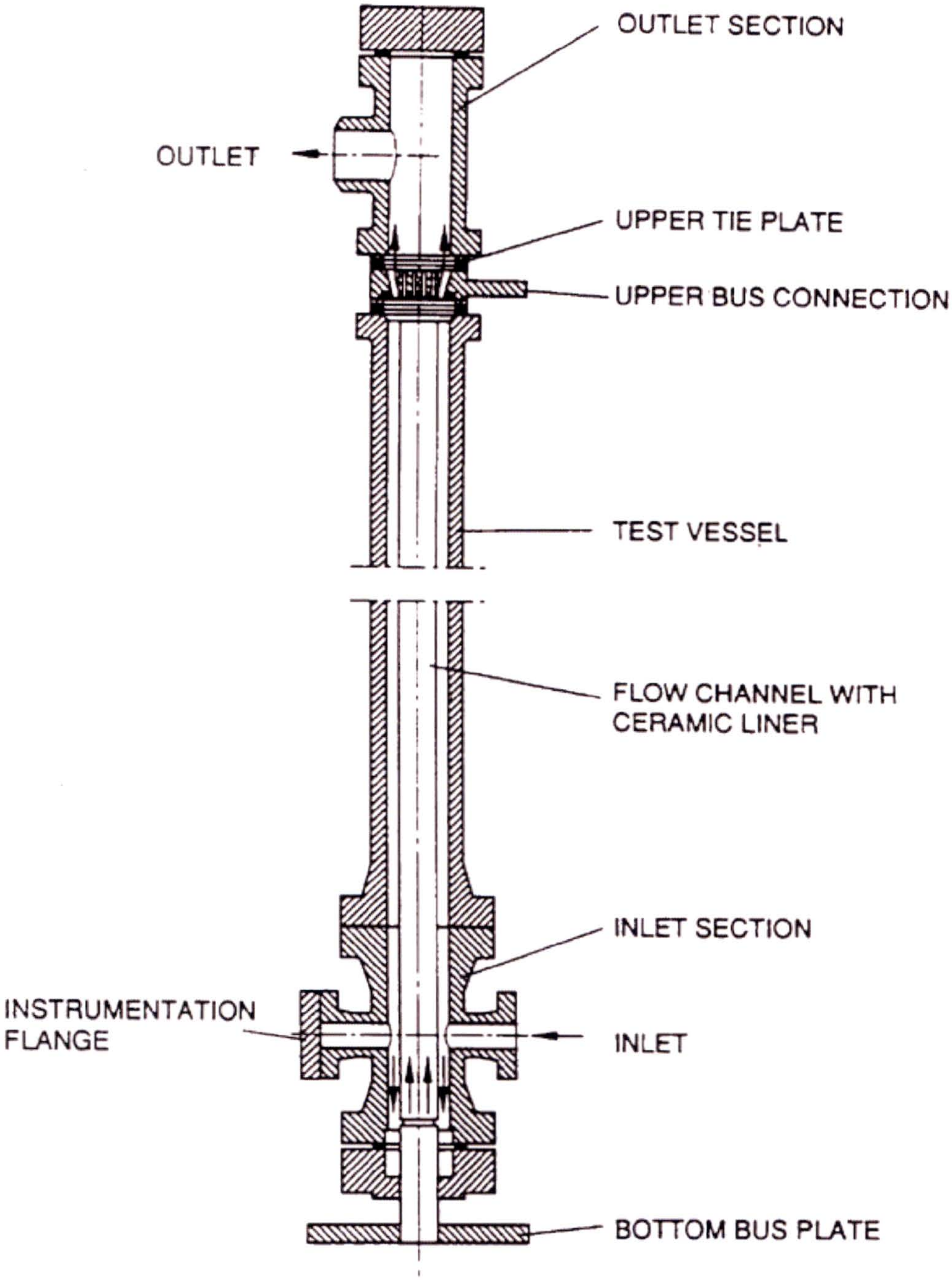

Figure 2. KATHY BWR Test Vessel

Question 2:

Please provide a description of benchmarks performed with KATHY against other testing facilities, as well as a reference to documents where these benchmarks are described in detail.

Response 2:

Two tests have been performed in KATHY test facility – STS 2.1 and STS 2.2 – to benchmark it versus corresponding ATLAS loop tests ATA 714C and ATA 714D. Tests have been run with the ATRIUM-9 bundle design, cosine axial power profile and similar radial power distribution (peaking pattern). The peaking pattern for the tests is shown in Figure 3. Figure 4 and Figure 5 show the comparison between ATLAS and KATHY loop tests. The mean value close to unity and the low standard deviation for both peaking patterns confirms that the KATHY loop and ATLAS loop provide equivalent results. The KATHY loop was successfully benchmarked.

The benchmark is documented in [ ]

[ ]

Figure 3. Peaking Patterns for Benchmark Tests

[ ]

Figure 4. Comparison Between KATHY and ATLAS Loop Tests STS 2.1 and ATA 714C

Figure 5. Comparison Between KATHY and ATLAS Loop Tests STS 2.2 and ATA 714D

Question 3:

Only [ ] *were tested in the development of the ACE/ATRIUM 11 correlation. Please provide a justification for not testing* [ ].

Response 3:

The influence of [ ] on critical power has been quantified by experimental data collected for each fuel assembly design that has been licensed.

[

]

[ ]

[ ]

Table 1. Characteristics of Designs Suitable for Fitting

[ ]

[ ]

Table 2. Tests for Correlation Fitting and Validation

[ ]

Table 3. Number of Data Points in Each Data Base

[ ]

Table 4. Summary of ECPR Results

[ ]

Table 5. [ ] Prediction Accuracy Results

[ ]

[ ]

Figure 6. Lattice and Part Length Rod Positions

Question 4:

Please discuss the range of tested transient conditions, specifically including a discussion of [ ].

Response 4:

The ACE/ATRIUM 11 correlation is a steady-state correlation constructed from [ ] A limited amount of transient data is collected only for the purpose of validating the correlation under transient conditions. The kinds of transients that are performed are based on parametric effects of the principal boundary conditions pressure and mass flow rate.

Margin to critical power increases as the flow rate is increased. Therefore, one of the principal transient types is the flow decreasing transient.

Margin to critical power decreases as the pressure is increased. Therefore, one of the principal transient types is a pressure increase transient, with an associated power increase.

In BWR, pressure decreasing transients are not CPR limiting – the CPR margin actually increases from the start of the transient. There is a detailed discussion of BWR pressure decreasing transients and the applicability of the [ ] in Reference 3, RAI #16.

Question 5:

Please provide additional justification for the use of [ ] *up to* [ ] *when the highest tested* [ ] *is* [ ].

Response 5:

All ACE correlations have been developed utilizing the [

]

Table 6. [ ]

[ ]

[ ]

[

]

Table 7. KATHY Tests for [ ]

[

]

[ ]

[ ]

Figure 7. Critical Power vs. [ ] for ATRIUM-10

[ ]

Figure 8. Critical Power vs. [ ] for ATRIUM 10XM

[ ]

Figure 9. Critical Power vs. [ ] for ATRIUM 11 [ ]

Figure 10. Critical Power vs. [ ] calculated by ACE/ATRIUM 11 [ ]

Table 8. [ ] of ATRIUM Fuel Assembly Designs for Cosine Axial Power Profile

[ ]

Table 9. Impact on Critical Power Due to the Uncertainty of the [ ]

[ ]

Question 6:

Please provide additional details on the method used to develop [ ]. *Any response should discuss* [ ].

Response 6:

A part of the critical power test program is specifically designed to determine [ ]

[ ]

[ ]

Question 7:

As discussed in Section 9.0 of ANP-10335P, the [ ] in the test assembly is different from that of the production assembly. Please provide additional justification for why a correlation developed with this difference in the test assembly would be applicable to a production assembly. Any justification should specifically address the parameters that could be affected by such a difference and the approximate magnitude of the impact.

Response 7:

Since the test assembly is heated directly, an electrical current flows through the rods.

[

]

Question 8:

Please provide a brief discussion of the procedures for measuring steady-state and transient critical power data points. Also provide references to documents discussing the critical power test procedures in further detail, including the conditions required to ensure stability and the criterion for determining that dryout has occurred.

Response 8:

Steady-state Testing

The methodology developed for performing dryout testing is fairly standard. The procedure is described in [ ] and applied for all tests.

[ ]

Transient Testing

Transient dryout tests are performed according to a transient test specification [ ], which defines the test bundle, the initial conditions and [ ]

Question 9:

Please provide additional information about the design of the ACE/ATRIUM 11 critical power tests, including a discussion of how bias was eliminated from the testing program. Page 7-9 of ANP-10335P referenced full map, partial map, and statistical design of experiments tests – please define each of these terms and discuss how the experimental design differs between them. Also, please include a reference for a document discussing procedures for design of experiments for the KATHY loop.

Response 9:

ATRIUM 11 consists of an 11x11 square array of rods. It contains 92 full length rods, 12 short part length rods, 8 long part length rods, and one central water channel that occupies a 3x3 array. Due to the 1/8 symmetry of the fuel assembly, there are 13 unique positions for the full length rods, 3 unique positions for the short part length rods and 2 unique positions for the long part length rods. [

]

The process of critical power correlation development is described in AREVA Operating Procedure [ ] of the Fuel Business Unit. After defining a List of Requirements for the correlation – e.g. fuel assembly geometry, correlation form, application range, licensing requirements, and I&C requirements – a Design Technical Specification Document is issued including the scope of the test program. The adequacy of the test program for ACE/ATRIUM 11 has been formally reviewed and approved within AREVA.

For the design of the ATRIUM 11 tests, [

]

[ ]

Figure 11. [ ] Regions of ATRIUM 11 [ ]

Critical power tests for ATRIUM 11 have been designed to obtain data:

[ ]

The test program is also intended to cover the range of applicability, including:

[ ]

In total, [ ] have been measured for ACE/ATRIUM 11 correlation development and validation (see Table 10). All the above mentioned objectives for the ATRIUM 11 critical power test have been met. Compared to ATRIUM 10XM the

[

]

Table 10. ATRIUM 10XM and ATRIUM 11 Test Program Comparison

[ ]

Standard map has been applied for the tests [

]

Statistical design of experiments (SDE) has been applied for the tests [

] SDE consists of [

]

Full map has been applied for the tests [ ] Full map contains data at [

]

Partial map has been measured [

]

[

]

Table 11. Maps Tested for Different [ ]

[ ]

Table 12. Maps Tested With [ ]

[ ]

Table 13. Data Density [ ]

[ ]

Question 10:

Please provide the values of measurement uncertainties in the KATHY loop, with a focus on the uncertainties in the parameters discussed in Section 6.13 of ANP-10335P. Please also provide a brief discussion of how each value was derived.

Response 10:

The measurement uncertainties of the experimental variables are:

Question 11:

Please provide a discussion of the instrumentation provided in the KATHY loop. The information provided should include a brief discussion of how diversity and redundancy of key measurements are ensured.

Response 11:

In order to provide experimental data for critical power correlation development reliable measurements are required for the [

] and bundle power. All these measurements are performed by calibrated and redundant measurement devices. In addition [

]

[

]

[

]

Bundle power

Electrical bundle power is the product of the electrical current and voltage.

1. Voltage measurement

   [

   ]

2. Electrical current measurement

   [

   ]

Question 12:

Please briefly describe the calibration of the instruments at the KATHY facility, including the frequencies of instrument calibration and reasons for those frequencies. Please also include a reference to a document describing the calibration in detail.

Response 12:

Calibration for the sensors is done in the calibration lab. The calibration lab has a controlled and monitored environment. Calibration for the DAQ-channels is [

]

Question 13:

Please discuss the uncertainties associated with measurement of critical power in both steady-state and transient testing. Any response should include a quantification of the measurement uncertainty and a description of how the value was obtained.

Response 13:

The ACE critical power correlation is a [ ] correlation. [ ] To apply the correlation to a particular fuel design, design specific data are needed to determine the correlation coefficients.

[ ]

Steady-state Measurement Uncertainty

The steady-state critical power measurement uncertainty is determined [ ]

[ ]

[ ]

Transient Test Measurement Uncertainty

For licensing the critical power correlation, transient measurements were used [ ]

Question 14:

Please discuss the heat losses from the test section, including how these losses vary depending on key parameters (test section power, flow rate, etc.).

Response 14:

In the KATHY loop, the heater rod bundle is housed in a ceramic liner. This liner serves to simulate the flow channel and to electrically insulate the spacers from each other.

[

]

The heat losses of the KATHY Loop have been analytically evaluated and are experimentally checked at the beginning of every testing day. Generally, the test section heat losses depend on [

] For thermal equilibrium conditions (long term heat losses), test section heat losses depend on the temperature difference across the test vessel insulation.

In order to achieve thermal equilibrium (quasi steady state temperature profile in the test section and ring chamber), [ ]

In the heat balance measurements, the bundle power is compared to the enthalpy change between the test section inlet and outlet. For single phase flow, the difference between the two parameters is equal to the test section heat loss. In order to prevent water evaporation in the heat balance measurements, inlet enthalpy is kept sufficiently low. For ATRIUM 11 tests, the average value of the experimentally determined heat loss is [ ] the standard deviation is [ ]. Compared to the measured critical power [ ] these heat losses are negligible and the magnitude is less than [ ]

[ ]

Both the analytical estimate and the measurements show that the heat loss of the test loop during the critical power testing is quite small.

Although the heat loss has been minimized through test facility design, AREVA does consider the heat loss to be important and therefore considers it important to monitor it during the BWR test programs. The frequent checks performed during the test program confirm that the test loop was operating as designed and that the experimental setup results in the expected level of heat loss. In the design of the KATHY loop, the temperature measurement that is applied to determine the inlet enthalpy is upstream of the test bundle. Figure 2 (RAI #1) shows that when the test vessel is reached the flow moves downward and then enters the rodded section of the bundle at the bottom. Figure 4.3 of ANP-10335P shows that between the lower tie plate and the upper tie plate, each full length rod has a lower end extension (low resistance), a high resistance section forming the heated length, and an upper end extension (low resistance). The part length rods are missing the upper end extension. The rod end extensions dissipate a small amount of heat that is proportional to the bundle power [

]

Question 15:

It is not clear how the initial conditions and boundary conditions for the ACE/ATRIUM 11 correlation were chosen. Please explain the initial and boundary conditions for the ACE/ATRIUM 11 correlation in further detail, especially including the [ ] *discussed in ANP-10335P Section 6.7.*

Response15:

[ ]

Question 16:

Please provide a discussion of the process used to fit the coefficients detailed in Section 6 of ANP-10335P. Since it is the staff's understanding that [ ], *the response should include a discussion of* [ ]. *The response could be a reference to an existing document.*

Response 16:

A description of the procedure for fitting of the coefficients of the ACE/ATRIUM-10 critical power correlation was provided in Reference 3 in Appendix A. This information was provided in response to Reference 3 RAI #3, #4, #5, #6, #7, #8, #9, #10, #31, and #35. The process describes the fitting of [ ] Once the process is complete (step 11), [ ] according to the method provided in the respective topical reports. This same process was used in the development of the ACE/ATRIUM 10XM correlation, Reference 7.

The assessment of the correlation for a particular [ ] includes an examination of the overall statistics, mean and standard deviation of ECPR, [ ]

[

]

The final ATRIUM 11 correlation has good behavior.

Question 17:

What is the criterion for determining [ ] in the second-to-last paragraph of Page 6-22 in ANP-10335P?

Response 17:

With the critical power correlation and a set of additive constants, the critical power correlation is applied to each measurement in the critical power data base defining data set. The critical power is calculated as the power that causes [

]

Question 18:

What was the purpose of the [ ]*? What is* [ ] *and how is it defined?*

Response 18:

[ ]

[

]

Table 14. STS119.01 Combined Statistics (Rod Position 28)

[

]

Question 19:

What is the basis for selecting [ ] of the data for correlation and [ ] for validation? How does [ ] impact the correlation uncertainty? The response should address both the ECPR uncertainty and the additive constant uncertainty.

Response:

AREVA enlisted the assistance of a prominent experimental heat transfer expert, Dr. Robert J. Moffat, Stanford University, to assist with formalizing the process for correlation development. The result of this collaboration was a formal correlation development guideline [ ]. It describes the need for partitioning a data set prior to correlation development. The basis for partitioning comes from Reference 12, Section 6.4.7.

> *"Sometimes it is not practical or possible to obtain additional data for model validation. In such cases, prior to model fitting, the complete data set is split into two subsets by some reasonable criterion. One subset is used to carry out the regression analysis and model development process, as discussed in the previous sections of this chapter. Once a satisfactory prediction equation has been developed, the other data set is used to validate it; that is, to see how well it predicts."*

Criteria for performing the partitioning are not provided in Reference 12. However the recommendation of Dr. Moffat was incorporated into Reference 24 and is a random selection of the data, placing [ ] in the defining data set and [ ] in the validating data set. Both References 12 and 24 state that partitioning into two data sets should not be performed if the number of data points is less than 2p+25 where p is the number of unknown coefficients being fit.

To investigate the effect of the choice of where to place each data point – defining or validating – the partition of the data was performed [ ]

[

]

Table 15. Overall Statistics Applying Multiple Partitions of Experimental Data

[

]

Question 20:

Please discuss in additional detail why it is considered appropriate [ ]. *Were* [ ] *discussed in Section 7.3 applied to the correlation during the uncertainty assessment?*

Response 20:

The results of [ ] are not used either in the fitting of the correlation or in the determination of the uncertainty. With respect to the ACE/ATRIUM 11 critical power correlation (and its predecessors), [ ] are used solely for the purpose of confirming that the correlation has the correct behavior.

[ ]

[

]

Now consider the dryout measurements. If one looks at the best estimate fit of the critical power correlation to the steady-state experimental critical power data, it is observed that [

] This is expected.

Consider the hypothetical case where [

]

[

] provide a confirmation that the behavior of the ACE/ATRIUM 11 correlation is as expected.

[

]

Question 21:

The topical report states in Section 6.13.1 that there is no lower limit on [
]. *Does AREVA plan to use the ACE/ATRIUM 11 correlation* [
below]? *If so, please provide additional justification.*

Response 21:

The ACE critical power correlation cannot be applied to [

] The correlation is implemented in a software library that is named ACELIB. ACELIB checks against [

]

Question 22:

Does AREVA plan to use the ACE/ATRIUM 11 correlation at [ ] greater than [ ]? If so, will some kind of upper limit on [ ] actually be applied?

Response 22:

For limiting and near limiting assemblies, a [ ] is applied. [ ]

No upper limit is imposed on [ ]

Question 23:

Please clarify when the [ ] *will be applied.*

Response 23:

[ ]

Question 24:

Please provide plots of the computational domain. These plots should use pairs of the key parameters ([ ]) for the x-axes and y-axes. Separate versions of the plots should be included for the correlation and validation data, as well as the combined dataset. Each plot should also include lines denoting the computational range of each parameter.

For each obvious region that lacks experimental data (especially validation data) lying within the computational domain, please justify why it is not possible to enter this region in an operating reactor. Alternatively, justify the correlation's behavior in the region.

Response 24:

The computational domain plots are provided in Figure 12 through Figure 17 (combined data set), Figure 18 through Figure 23 (Defining data set), and Figure 24 through Figure 29 (Validating Data Set). The range of applicability of the ACE/ATRIUM 11 critical power correlation is shown by dashed lines in these plots. The critical power measurements are shown by symbols. The domain range of the application of the critical power correlation to limiting or near limiting assemblies is shown by a box.

The application data are [ ]

The [ ] are covered well by the experimental data.

[ ]

[

]

All areas of the range of applicability are adequately covered as described in Reference 2.

[ ]

Figure 12. Computational Domain of [ ] (Combined)

[

]

**Figure 13. Computational Domain of [
] (Combined)**

[

]

**Figure 14. Computational Domain of [
] (Combined)**

[

]

Figure 15. Computational Domain of [ ] (Combined)

[

]

Figure 16. Computational Domain of [ ] (Combined)

[ ]

Figure 17. Computational Domain of [ ] (Combined)

[ ]

Figure 18. Computational Domain of [ ] (Defining)

[

]

Figure 19. Computational Domain of [
] (Defining)

[

]

Figure 20. Computational Domain of [
] (Defining)

[

]

Figure 21. Computational Domain of [
] (Defining)

[

]

Figure 22. Computational Domain of [
] (Defining)

[

]

Figure 23. Computational Domain of [
] (Defining)

[

]

Figure 24. Computational Domain of [
] (Validating)

[ ]

Figure 25. Computational Domain of [ ] (Validating)

[ ]

Figure 26. Computational Domain of [ ] (Validating)

[ ]

Figure 27. Computational Domain of [ ] (Validating)

[ ]

Figure 28. Computational Domain of [ ] (Validating)

[

]

Figure 29. Computational Domain of [ ] (Validating)

Question 25:

Please provide additional explanation and justification of the trend of increasing ECPR standard deviation as a function of pressure. It is unclear to the NRC staff why this increasing variability should result from [ ], as discussed in Section 7.1.3 of ANP-10335P.

Response 25:

The reason given for the ACE/ATRIUM 11 critical power correlation standard deviation increasing as a function of pressure is [ ] It was concluded that the correlation uncertainty is adequate. The basis for this conclusion comes first from [ ] and second, [ ]

[ ]

The ECPR data of the combined data set is binned by test and pressure (Table 16).

[ ]

[

]

Consider now if this behavior is a characteristic of only ACE/ATRIUM 11. A similar examination is performed with ACE/ATRIUM 10XM, binning the combined data set by test and pressure, as shown in Table 17. [

]

[

]

Table 16. ATRIUM 11 ECPR Binned by Test and Pressure (Combined)

[

]

Table 17. ATRIUM 10XM ECPR Binned by Test and Pressure (Combined)

[ ]

Question 26:

Please justify why the [ ] *is considered poolable, considering that the mean and standard deviation of the ECPR vary significantly between* [ ]. *Please also discuss why the* [ ] *provided in* [ ] *do not appear to appropriately match the data.*

Response 26:

[

]

[

] In general, unlike in a PWR CHF correlation topical report, no design limit will be found in the ACE/ATRIUM 11 topical report. In BWR, the safety limit is determined by a separate methodology (Reference 11). The essential uncertainty of the dryout correlation that goes into the safety limit methodology and calculation is [

]

[ ]

Figure 30. ECPR as Function of [ ]

Table 18. Statistics by [ ]

[ ]

Question 27:

There appears to be a non-conservative subregion between [ ] on Figures 7.1 and 7.9. There is another potentially nonconservative region at [ ]. Please justify why it is acceptable to use the correlation in these areas. Any discussion should address how the correlation uncertainties presented in the topical report account for the uncertainty in these areas.

Response 27:

The data points that are identified as lying in the range of power of [

]

The safety limit methodology is designed to work in conjunction with the critical power correlation to develop an accurate MCPR SL.

Question 28:

Please provide additional justification for why it is appropriate to represent the ACE/ATRIUM 11 uncertainty with the ECPR distribution determined from the [ ] rather than the [ ]. The response should discuss how the correlation uncertainties will be applied in other methodologies.

Response 28:

The reason that the [ ] is used to determine the additive constant uncertainty is [ ]

Each additive constant must be determined from applicable data. Reference 12, Section 6.4.7 page 363 says that partitioning should not be performed if the number of data points is fewer than 2p+25 where p is the number of unknown coefficients to be fitted. [ ]

The data and method being applied to determine the additive constant uncertainty came about in the process of addressing a non-conformance described in Reference 14. The summary stated "SPC failed to develop an adequate number of test points, and failed to test an adequate range of conditions to justify the uncertainty values for the 'additive constants' used in determining the SLMCPR for the ATRIUM-9 fuel design." The methodology for determining the additive constant uncertainty and insuring sufficient data are available for this was developed as part of resolving this non-conformance.

Question 29:

Will ACE/ATRIUM 11 be implemented in codes other than XCOBRA-T? If so, please discuss how it will be implemented and provide the criteria that will be used to demonstrate that the implementation was appropriate.

Response 29:

The ACE correlation is implemented in a code library named ACELIB. All production codes that implement the ACE correlation use this library. Thus, it is assured that each code is using a single implementation of the correlation, thus eliminating errors that are the result of different implementations. ACELIB was also used to benchmark the ACE/ATRIUM 11 critical power correlation reported in Reference 2. The ACE/ATRIUM 11 critical power correlation is implemented in the steady-state core thermal-hydraulics code XCOBRA (Reference 15), the transient core thermal hydraulics code XCOBRA-T (References 16 and 17), the core 3D simulator MICROBURN-B2 (Reference 18), the MCPR safety limit calculation code SAFLIM-3D (Reference 11), the LOCA code RELAX (Reference 19), and BWR transients code AURORA-B (Reference 20).

The installation of the correlation in a code can be checked against the benchmarking. For the same power distribution and nodalization, and the same steady-state boundary conditions provided to ACELIB, the results should match the benchmark. However small (but insignificant) differences can be observed when different computing hardware and software platforms are used, or when different FORTRAN or C compilers are applied, as a result of round-off errors. [

]

Question 30:

Figures 2.1, 7.1, and 7.9 use units of kW. Were these intended to be MW?

Response 30:

Yes. The correct units for these three plots are "MW". Updated plots are provided in Figure 31 to Figure 33. The updated plots will be placed in the topical report.

[ ]

Figure 31. Comparison of Calculated to Measured Critical Power Data for the ATRIUM 11 Fuel Design

Figure 32. Calculated vs. Measured Critical Power (Defining)

Figure 33. Calculated vs. Measured Critical Power (Validating)

2.0 REFERENCES

General References

1. J. G. Rowley, "Request for Additional Information RE: AREVA Inc. Topical Report ANP-10335P/NP, 'ACE/ATRIUM 11 Critical Power Correlation' (TAC No. MF5841)," Letter to Gary Peters, Director, Licensing and Regulatory Affairs, AREVA Inc., dated April 11, 2016.

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4. "General Electric BWR Thermal Analysis Basis (GETAB): Data, Correlation and Design Application," General Electric Co. Report No. NEDO-10958-A, January 1977.

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13. J.C.M. Leung, "Critical Heat Flux Under Transient Conditions: A Literature Survey," NUREG/CR-0056, June 1978.

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17. XN-NF-84-105(P)(A) Volume 1 Supplement 4, "XCOBRA-T: A Computer Code for BWR Transient Thermal-Hydraulic Core Analysis Void Fraction Model Comparison to Experimental Data," Advanced Nuclear Fuels Corporation, June 1988.

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20. ANP-10300P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Transient and Accident Scenarios," December 2009.

[ ]

[ ]

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AREVA

March 30, 2017
NRC:17:016

U.S. Nuclear Regulatory Commission
Document Control Desk
11555 Rockville Pike
Rockville, MD 20852

Revision to Supplemental Information Regarding Topical Report ANP-10335P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation"

AREVA Inc. (AREVA) requested the NRC review and approval of Topical Report (TR) ANP-10335P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation" in Reference 1. Supplemental information was provided in Reference 2 to qualify the ACE/ATRIUM 11 critical power correlation for use with the AURORA-B Methods. The attached enclosures revise the information transmitted to the NRC in Reference 2 to correct errors in the data and to respond to draft RAI questions which were transmitted by email in Reference 3. The revised enclosures completely replace those transmitted in Reference 2, therefore only revision 1 of the enclosures will be included in the approved version of the topical report.

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

There are no commitments within this letter or its enclosures.

If you have any questions related to this information, please contact Mr. Morris E. Byram by telephone at (434) 832-4665, or by e-mail at Morris.Byram@areva.com.

Sincerely,

Gary Peters

Gary Peters, Director
Licensing & Regulatory Affairs
AREVA Inc.

cc: J. G. Rowley
Project 728

References:

Ref. 1: Letter, Pedro Salas (AREVA) to Document Control Desk (NRC), "Request for Review and Approval of ANP-10335P Revision 0, 'ACE/ATRIUM 11 Critical Power Correlation'," NRC:15:012, February 27, 2015.

Ref. 2: Letter, Gary Peters (AREVA) to Jonathan Rowley (NRC), "Supplemental Information Regarding Topical Report ANP-10335P, Revision 0, 'ACE/ATRIUM 11 Critical Power Correlation'," NRC:16:039, December 21, 2016.

Ref. 3: Email, Jonathan Rowley (NRC) to Alan Meginnis (AREVA), "FW: Additional RAIs for ACE/ATRIUM 11 (MF5841)," January 17, 2017.

Enclosures:

1. Proprietary copy of ANP-10335Q2P, Revision 1, "ACE/ATRIUM 11 Critical Power Correlation - RAIs"
2. Non-Proprietary copy of ANP-10335Q2NP, Revision 1, "ACE/ATRIUM 11 Critical Power Correlation - RAIs"
3. Notarized Affidavit

AFFIDAVIT

COMMONWEALTH OF VIRGINIA)
) ss.
CITY OF LYNCHBURG)

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

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

3. I am familiar with the AREVA information contained in ANP-10335Q2P, Revision 1, entitled "ACE/ATRIUM 11 Critical Power Correlation RAIs," and referred to herein as "Document." Information contained in this Document has been classified by AREVA as proprietary in accordance with the policies established by AREVA Inc. for the control and protection of proprietary and confidential information.

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

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

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

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

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

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

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

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

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

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

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

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

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

Manuel E. Bejarano Jr.

SUBSCRIBED before me this 29th

day of March, 2017.

S McFaden

Sherry L. McFaden
NOTARY PUBLIC, COMMONWEALTH OF VIRGINIA
MY COMMISSION EXPIRES: 10/31/18
Reg. # 7079129

SHERRY L. MCFADEN
Notary Public
Commonwealth of Virginia
7079129
My Commission Expires Oct 31, 2018

0414-12-F04 (Rev. 001, 03/10/2016)

AREVA

ACE/ATRIUM 11 Critical Power Correlation RAIs

ANP-10335Q2NP
Revision 1

Topical Report

March 2017

AREVA Inc.

Nature of Changes

Item	Section(s) or Page(s)	Description and Justification
1	1-1	Introduction rewritten in entirety
2	2-1, 2-2	Correct errors in the text
3	2-3 to 2-6	Correct errors in Table 1
4	2-7	Correct errors in Table 2
5	3-1	New - add response to Draft RAI A
6	4-1	New - add response to Draft RAI B

Contents

List of Tables

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1.0 INTRODUCTION

AREVA is introducing a new fuel assembly design, the ATRIUM 11. To support its introduction, a critical power correlation, ACE/ATRIUM 11 was developed. This new correlation was provided to the U.S. NRC for review in February 2015 (Reference 1). A post-submittal meeting was held on May 12, 2015 that reviewed the test program and correlation development and provided an introduction to the topical report. An audit for understanding was conducted by the U.S. NRC staff on October 27 – 28, 2015 (Reference 2). Following this audit, 30 RAIs were received (Reference 3). AREVA provided the response to each of these 30 RAI's in August 2016 (Reference 4).

The critical power correlation is an essential component of the transient methodologies for determining ΔCPR and setting reactor licensee MCPR operating limits. The transient benchmarking of the ACE/ATRIUM 11 critical power correlation with the licensed transient code XCOBRA-T (Reference 5) was provided in Reference 1 (Section 7.3).

A new transient methodology, AURORA-B (Reference 6), based on S-RELAP5 is also under review by the NRC staff. It is AREVA's intention to apply the ACE/ATRIUM 11 critical power correlation with the AURORA-B transient methodology. The U.S. NRC requested that AREVA provide evidence justifying that the AURORA-B methodology could be applied to the ATRIUM 11 transient evaluation based on the ACE/ATRIUM 11 critical power correlation. To justify this application, AREVA provided the NRC a report benchmarking the S-RELAP5 code to the experimental transient data of ATRIUM 11 (Reference 8). This report was prepared as supplementary information to be considered with the response to RAI #29 (Reference 4) and was sent to the NRC in December 2016. In response to the S-RELAP5 transient benchmarking results, the NRC staff asked two additional questions. The questions were discussed with the NRC staff on January 30, 2017 to make sure that the questions were understood and to confirm that the proposed responses would address the NRC staff concerns.

This report is a revision to the Reference 8 document. The revision corrects errors in the presented data. The report has also been expanded to include the responses to the two additional NRC questions.

2.0 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 11 when using the ACE/ATRIUM 11 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. Reference 1, Figure 7.18, page 7.43 shows the forcing function characteristics for a typical LRNB test and Reference 1, Figure 7.19, page 7-43 shows the comparable forcing function characteristics for a typical loss of flow event.

A total of [ ] ATRIUM 11 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. Of these [ ] transient critical power tests, [

] The initial conditions for all of the tests are provided in Reference 1, Table 7.20, page 7-36.

The AREVA transient thermal hydraulic code S-RELAP5 (Reference 6), was used to predict the transient test results using the ACE/ATRIUM 11 critical power correlation. The test power forcing function provides the boundary condition of power, which is modeled in S-RELAP5 [ ]

[

]

The results are summarized in Table 1. [

]

Table 1 S-RELAP5 ACE/ATRIUM 11 Transient Dryout Results

[ ]

Table 1 S-RELAP5 ACE/ATRIUM 11 Transient Dryout Results (cont.)

[ ]

Table 1 S-RELAP5 ACE/ATRIUM 11 Transient Dryout Results (cont.)

[ ]

Table 1 S-RELAP5 ACE/ATRIUM 11 Transient Dryout Results (cont.)

[ ]

Table 2 S-RELAP5 K-Factor Iteration Results

[ ]

3.0 Draft RAI-A:

In ANP-10335Q2P, AREVA provided additional information to confirm that the ACE/ATRIUM 11 correlation provides conservative predictions of critical power within the S-RELAP5 transient thermal-hydraulic code. The RAI response detailed results from transient critical power testing, for which predictions were also made, to justify that the critical power correlation as applied within S-RELAP5 produces results that are conservative overall.

Of the [ ] *tested transients that were measured or predicted to go into boiling transition,* [ ] *transients were found to be non-conservatively predicted (i.e., the predicted time of boiling transition was found to be later than that which was measured in the test or no dryout was predicted at all). For each of these* [ ] *data points, AREVA determined* [

]. *For* [ ] *tests,* [
needed for a conservative prediction of
]. *However, for* [

].

It is the NRC staff's understanding of AREVA's safety limit minimum critical power ratio (SLMCPR) methodology, documented in ANP-10307PA, Rev. 0, "AREVA MCPR Safety Limit Methodology for Boiling Water Reactors," that [

]. *Given that* [

], *how does AREVA assure that the uncertainty in the ACE/ATRIUM 11 critical power correlation resulting from its application in S-RELAP5 is adequately captured in the safety limit?*

<u>AREVA Response A:</u>

The response to this question is provided in parts. First, the method of stratified random sampling (used in the safety limit methodology) will be described by an example and it will be compared to simple random sampling and shown to be an equivalent method for sampling normal distributions. In the second part, the safety limit methodology will be briefly described in the context of the examples. Finally, expectations on the behavior of

data points in the transient benchmarking to S-RELAP5 are described in the context of the critical power correlation uncertainty. Now consider the first part.

Stratified random sampling is applied in the Safety Limit methodology to improve the precision of the estimates of parameters describing the population. It is a method suitable for finite populations (e.g. number of fuel rods in nuclear reactor core) and it minimizes sample selection bias so that certain segments of the population are not over or under represented (e.g. under representing values in the tail of the normal distribution). The advantages of stratified random sampling are demonstrated by an example.

A population is constructed by collecting N=1000 random samples from a normal distribution whose mean is 1.0 and standard deviation is 0.2. The population is examined first by simple random sampling and then by stratified random sampling.

Simple Random Sampling of the Population

20 samples are collected from the population using the Simple Random Sampling (SRS) method (Table 3).

The mean of these n=20 samples is calculated (Reference 7, page 5)

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i = \frac{1}{20}\sum_{i=1}^{20} x_i = 1.0079 \tag{1}$$

The sample standard deviation is calculated (Reference 7, page 9)

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} = \sqrt{\frac{1}{20-1}\sum_{i=1}^{20}(x_i - 1.0079)^2} = 0.2242 \tag{2}$$

The standard error (SE) is calculated (Reference 7, page 104)

$$SE = \frac{s}{\sqrt{n}} = \frac{0.2242}{\sqrt{20}} = 0.0501 \tag{3}$$

The behavior of the "mean" statistic as a function of the number of samples is shown in Figure 1 along with the standard error bounds. The standard deviation as a function of the number of samples is provided in Figure 2.

Stratified Random Sampling of the Population

An alternative strategy, stratified random sampling, is applied to the population. The domain of the normal distribution is divided into L=5 non-overlapping strata as shown in Figure 3. The boundaries for the strata are chosen such that any single random sample has equal probability of falling within each of the strata. Thus, the probability (area under the curve) of each strata is equal to 0.2. For a normal distribution with a mean of 1.0 and standard deviation of 0.2, the boundaries of the strata are defined in Table 4.

The population of each strata is

$$N_h = \frac{N}{L} = \frac{1000}{5} = 200 \tag{4}$$

Within each strata, n_h random samples are collected. Four random samples are collected from each of the five strata and placed in Table 5.

The mean value within each strata is calculated

$$\overline{x}_h = \frac{1}{n_h} \sum_{i=1}^{n_h} x_{ih} \tag{5}$$

and shown in Table 6. The combined mean of the stratified samples is calculated (Reference 7, page 476)

$$\overline{x} = \sum_{h=1}^{L} \left(\frac{N_h}{N} \right) \overline{x}_h = \frac{200}{1000} \left(0.7720 + 0.9071 + 0.9881 + 1.1021 + 1.2977 \right) = 1.0134 \tag{6}$$

The standard deviation within each of the strata is calculated

$$s_h = \sqrt{\frac{1}{n_h - 1} \sum_{i=1}^{n_h} \left(x_{ih} - \overline{x}_h \right)^2} \tag{7}$$

and is provided for each strata in Table 7. The standard error is calculated (Reference 7 page 476)

$$
\begin{aligned}
SE &= \sqrt{\sum_{h=1}^{L}\left(\frac{N_h}{N}\right)^2\left(\frac{s_h^2}{n_h}\right)\left(\frac{N_h-n_h}{N_h}\right)} \\
&= \sqrt{\left(\frac{N_h}{N}\right)^2\left(\frac{1}{n_h}\right)\left(\frac{N_h-n_h}{N_h}\right)\sum_{h=1}^{L}s_h^2} \\
&= \sqrt{\left(\frac{200}{1000}\right)^2\left(\frac{1}{4}\right)\left(\frac{200-4}{200}\right)\left(0.0851^2+0.0361^2+0.0473^2+0.0200^2+0.0884^2\right)} \\
&= 0.0136
\end{aligned}
\tag{8}
$$

The "mean" statistic as a function of number of samples from stratified random sampling is provided in Figure 4 along with the standard error bounds. In comparing Figure 1 to Figure 4, it is observed that for a prescribed number of samples, stratified random sampling produces a more accurate estimate of the mean than simple random sampling.

The standard deviation as a function of the number of samples taken is provided in Figure 5. Comparing to Figure 2, it is observed that an accurate estimate of the standard deviation is obtained faster with stratified random sampling than it is with simple random sampling.

Each of the strata represents a sub-population. That sub-population has a characteristic "mean" value. The mean value occurs at the centroid of each of the strata. For the population whose mean is 1.0 and standard deviation is 0.2 (Figure 3), the centroid values are provided in Table 8. [

] The stratification method is theoretically sound since the standard deviation of the normal distribution is not disrupted and it ensures accurate code results with a limited number of trials.

The example above demonstrates that stratified random sampling of a normal distribution provides the same result as would be obtained if simple random sampling is applied except that a good accuracy can be obtained from stratified random sampling with significantly fewer samples than are required with simple random sampling.

Safety Limit Methodology Sampling Methodology

The methodology for sampling uncertainty of significant variables in the Safety Limit Methodology makes use of the stratified random sampling method. The description taken from Reference 10, Section 3.4.1 is:

> *The normal distribution is modeled by a statistical stratification method.* [
>
>]

Figure 3-2 from Reference 10 has been reproduced in this document as Figure 6 . The safety limit methodology applies a Monte Carlo method for perturbing important parameters by their uncertainty. The additive constant uncertainty (and the other sampled parameters) are modeled with a normal distribution. The sampling performed in the safety limit methodology is based on the stratified random sampling methodology described in the example above.

[

]

[

] This conclusion is consistent with the example shown above.

Transient Benchmarks With S-RELAP5

Now consider the additive constant uncertainty and what it represents. This uncertainty is a 1σ value and only 68.3% of the values fall within ±1σ and only 95.5% of the values are expected to fall within ±2σ. If there were no conservatism in the application of the steady-state critical power correlation to transients, it would be expected that [ ] of the [ ] transients conducted would have values that fall outside of ±2σ. However, in the worst case of the S-RELAP5 transient benchmark calculations, the change in additive constant required to achieve a conservative result is only [ ] times the additive constant uncertainty [ ]. At this level, the number of expected values out of [ ] that are expected to fall outside the interval [ ] in a standard normal distribution is [ ] values. The observed number (on the non-conservative side) is [ ]. Thus, these results confirm that the application of the ACE/ATRIUM 11 critical power correlation, to XCOBRA-T and to S-RELAP5, is conservative.

The additive constant uncertainty is determined from steady-state measurements. It includes experiment uncertainty and model uncertainty. It would be expected that in a transient application there would be [ ]. But the S-RELAP5 (Section 2.0) and XCOBRA-T (Reference 1, Section 7.3, page 7-33) benchmark calculations show the inherent conservatism that results from applying a steady-state critical power correlation in transients (Reference 4, RAI #20, page 59), [ ]. Therefore, the uncertainty in the ACE/ATRIUM 11 critical power correlation applied within the SLMCPR calculation adequately covers [ ].

Table 3 Simple Random Sample of Size 20

i	x_i
1	1.2460
2	0.4820
3	1.0622
4	1.2958
5	1.2953
6	0.9767
7	1.1311
8	0.9831
9	0.9509
10	0.5793
11	1.2597
12	0.7346
13	0.9285
14	0.9865
15	0.8877
16	1.0345
17	0.8922
18	1.2597
19	1.0656
20	1.1059

Table 4 Strata Boundaries

	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5
Minimum	-∞	0.8317	0.9493	1.0507	1.1683
Maximum	0.8317	0.9493	1.0507	1.1683	+∞

Table 5 20 Random Samples – 4 per Strata Times 5 Strata

i	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5
1	0.8095	0.8654	0.9991	1.1126	1.2880
2	0.8250	0.9349	0.9517	1.0842	1.3394
3	0.8087	0.8885	0.9509	1.1251	1.3843
4	0.6448	0.9397	1.0505	1.0865	1.1789

Table 6 Sample Mean For Each Strata

	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5
$\overline{x}_h$	0.7720	0.9071	0.9881	1.1021	1.2977

Table 7 Sample Standard Deviation for Each Strata

	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5
s_h	0.0851	0.0361	0.0473	0.0200	0.0884

Table 8 Centroids of Strata

	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5
Centroid	0.7437	0.8951	1.0000	1.1049	1.2563

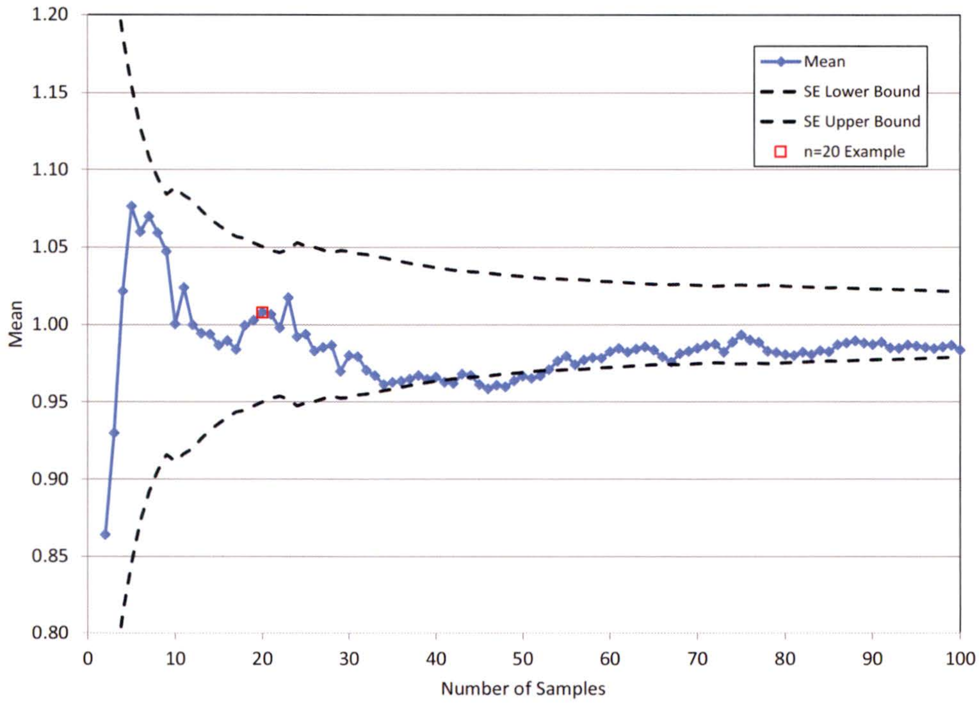

Figure 1 Simple Random Sampling Mean and Standard Error Bound

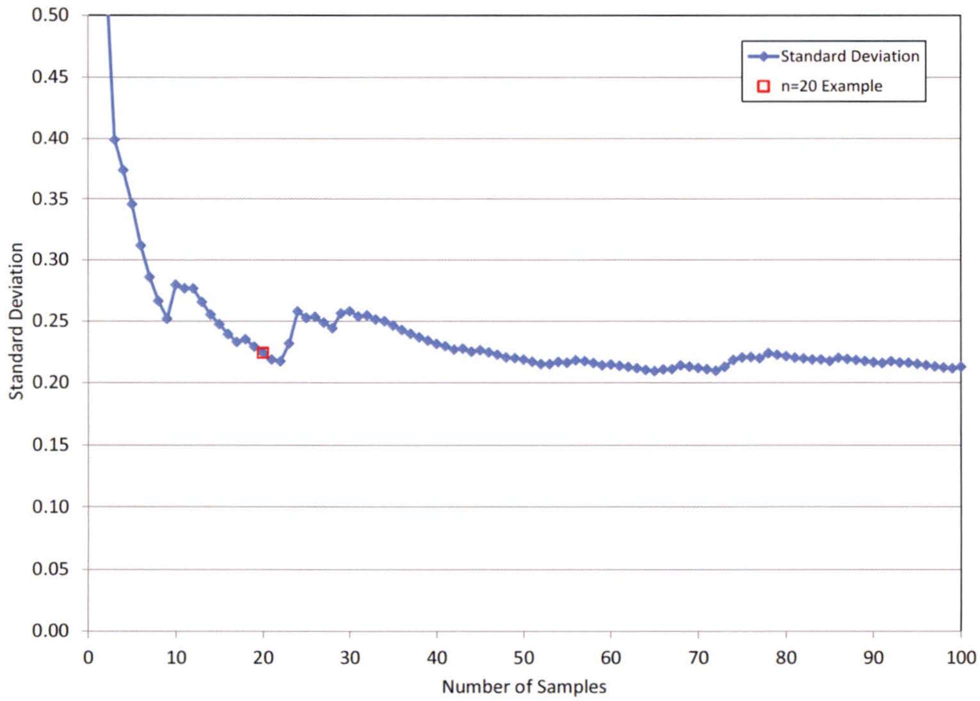

Figure 2 Simple Random Sampling Standard Deviation

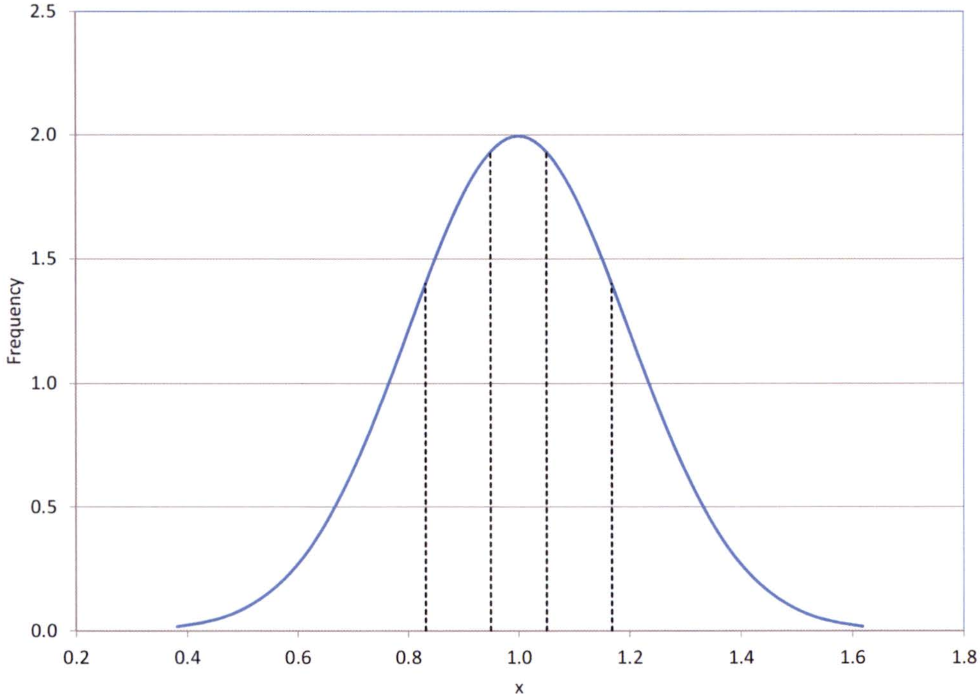

Figure 3 Population Strata

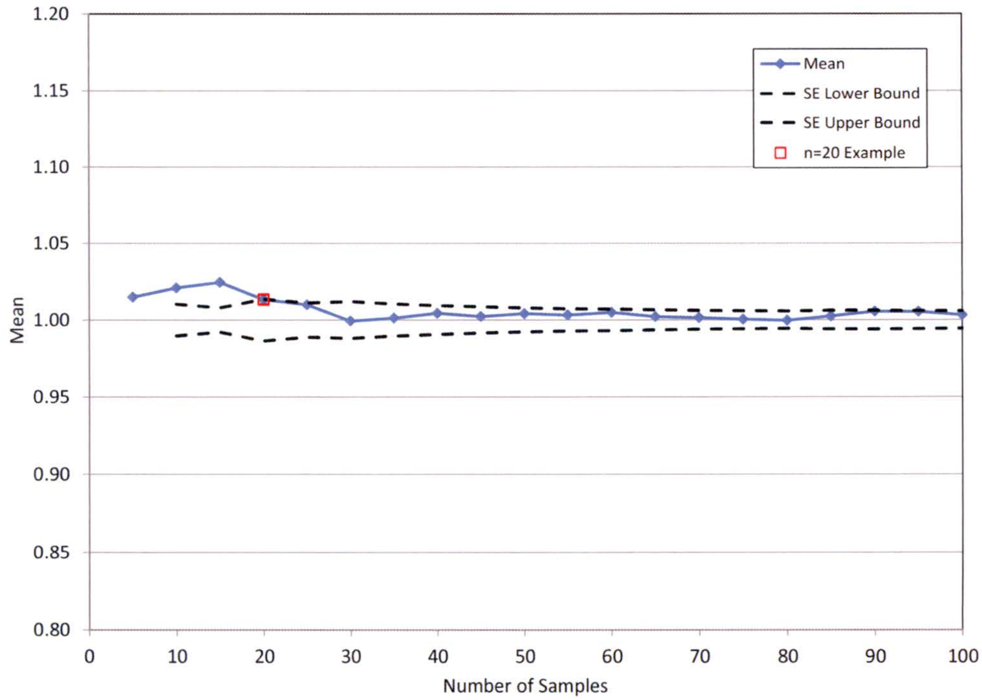

Figure 4 Stratified Random Sampling Mean and Standard Error Bound

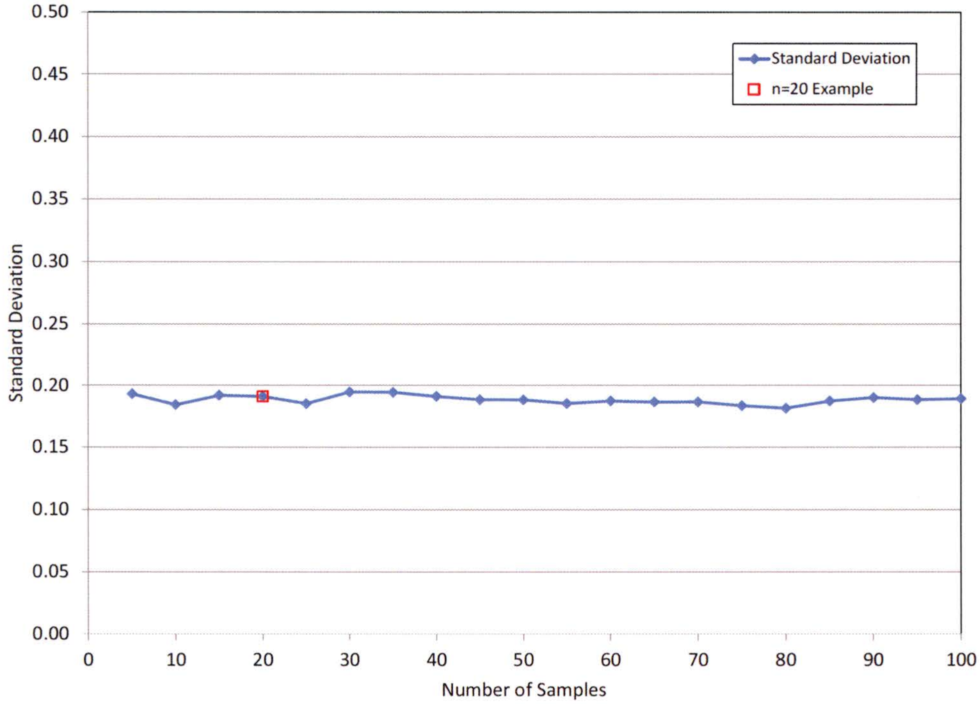

Figure 5 Stratified Random Sampling Standard Deviation

Figure 6 Stratified Normal Distribution Curve

4.0 Draft RAI-B:

Though the predictions of time to boiling transition for the transient testing presented in ANP-10335Q2P for S-RELAP5 are similar to those presented in ANP-10335P for XCOBRA-T, there are clear differences in the results between the two codes. In deriving the MCPR safety limit, there appears to be an
[
within] *to be addressed in the ΔCPR calculation. Considering that different codes are used, how does AREVA ensure that* [

] *?*

<u>AREVA Response B:</u>

It is expected that there would be some differences in the benchmark results between S-RELAP5 (Reference 8) and XCOBRA-T (Reference 4, Section 7.3, page 7-33). S-RELAP5 features a six equation model and XCOBRA-T features a three equation model. Each has different constitutive relations. This difference is recognized in the correlation development and qualification process by requiring that the critical power correlation be benchmarked prior to use in a new transient code.

It is assumed that [

]. In the response to Draft RAI A it is demonstrated that statistically the transient measurements are conservatively modeled relative to the [
]. The inherent conservatism in applying a steady-state correlation to transients is [
]. This conclusion is derived from code specific benchmarking to transient measurements.

Core monitoring is performed with MICROBURN-B2 (Reference 9). Transients start from a steady-state condition determined by MICROBURN-B2. This ensures that the change (ΔCPR) is derived from a reference condition that is being monitored. The SLMCPR calculation includes MICROBURN-B2 as a key element in the calculations. This assures that the SLMCPR derived from the SAFLIM3D is based on a reference

condition that is being monitored. This methodology provides assurance that the appropriate limit is determined and that the monitoring is performed to that limit.

5.0 REFERENCES

1. ANP-10335P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation," February 2015.
2. "Audit Plan For Audit for Understanding on ANP-10335P, 'ACE/ATRIUM 11 Critical Power Correlation,' TAC No. MF5841" Memorandum from Jeremy L. Dean to Anthony J. Mendiola, October 1, 2015.
3. "Request for Additional Information RE: AREVA Inc. Topical Report ANP-10335P/NP, 'ACE/ATRIUM 11 Critical Power Correlation,' (TAC No. MF5841)," Letter to Gary Peters, Director, Licensing and Regulatory Affairs, AREVA Inc., dated April 11, 2016.
4. ANP-10335Q1P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation – RAIs," August 2016.
5. XN-NF-84-105(P)(A) Volume 1 and Volume 1 Supplements 1 and 2, "XCOBRA-T: A Computer Code for BWR Transient Thermal-Hydraulic Core Analysis," Exxon Nuclear Company, October 1986.
6. ANP-10300P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Transient and Accident Scenarios," December 2009.
7. "Statistical Methods for Nuclear Material Management," NUREG/CR-4604, December 1988.
8. ANP-10335Q2P Revision 0, "ACE / ATRIUM 11 Critical Power Correlation RAIs," February 2015.
9. EMF-2158(P)(A) Revision 0, "Siemens Power Corporation Methodology for Boiling Water Reactors: Evaluation and Validation of CASMO-4 / MICROBURN-B2," October 1999.
10. ANP-10307PA, Revision 0, "AREVA MCPR Safety Limit Methodology for Boiling Water Reactors," June 2011.

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

October 4, 2017

Mr. Gary Peters, Director
Licensing and Regulatory Affairs
AREVA Inc.
3315 Old Forest Road
Lynchburg, VA 24501

SUBJECT: REQUEST FOR ADDITIONAL INFORMATION REGARDING AREVA INC. TOPICAL REPORT ANP-10335P/NP, REVISION 0, "ACE/ATRIUM 11 CRITICAL POWER CORRELATION" (TAC NO. MF5841)

Dear Mr. Peters:

By letter dated February 27, 2015 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML15062A553), AREVA INC. (AREVA) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review and approval Topical Report ANP-10335P/NP, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation." Upon review of the information provided, the NRC staff has determined that additional information is needed to complete the review. On September 7, 2017, Morris Byram, AREVA Product Licensing Manager, and I agreed that the NRC staff will receive the response to the enclosed Request for Additional Information (RAI) questions within 30 days from the date of this letter.

If you have any questions regarding the enclosed RAI questions, please contact me at 301-415-4053.

Sincerely,

Jonathan G. Rowley, Project Manager
Licensing Processes Branch
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 728

Enclosure:
RAI Questions

REQUEST FOR ADDITIONAL INFORMATION

RELATED TO TOPICAL REPORT ANP-10335P, REVISION 0

"ACE/ATRIUM 11 CRITICAL POWER CORRELATION"

AREVA INC.

(CAC NO. MF5841)

BACKGROUND

Over the course of the review of Topical Report ANP-10335P, Revision 0, the NRC staff became aware of a leaking fuel rod at the Kernkraftwerk Leibstadt (KKL) nuclear power plant in Switzerland, a boiling water reactor/6 (BWR/6) plant operating on yearly cycles. The leaker was believed to have resulted from excessive cladding oxidation due to dryout. Subsequent inspections found widespread occurrences of dryout in locations throughout the core. In the next cycle, steps were taken to increase the minimum critical power ratio operating limit and prevent future instances of dryout. However, further inspections revealed even more dryout indications after the compensatory measures were taken. Additional inspections found that dryout had occurred in several cycles before the leaking fuel rod was identified.

The dryout indications were characterized by visible, wedge-shaped areas of increased oxidation on the fuel rods. The size, shape, and material properties of these areas of increased oxidation indicate that dryout occurred over an extended period of time while the reactor was operating at steady-state conditions, with cladding temperatures remaining below 800°C. Though the shape of the oxidized areas was consistent, the dimensions of the oxidized area and the oxide thickness varied. Dryout is believed to have occurred only when the reactor operated at greater than 95 percent of rated total core flow and was only observed in first-cycle bundles that had been operated with a fuel assembly power greater than 7.4 megawatts. Within these bundles, dryout indications were only found on certain symmetric rod positions and always in the upper part of the bundle.

Dryout of the type observed at the plant was not observed in critical power testing at similar bundle flow rates and powers. At no point during KKL's operation did the analytical methods developed by the fuel's vendor predict that margin to dryout would be sufficiently degraded for dryout to occur. Currently, the underlying mechanisms that caused the dryout at KKL are still unknown.

RAI-SNPB-33

Given this operating experience, how does AREVA provide reasonable assurance that adequate critical power margin will be maintained during normal operation, including the effects of anticipated operational occurrences?

Enclosure

AREVA

October 27, 2017
NRC:17:044

U.S. Nuclear Regulatory Commission
Document Control Desk
11555 Rockville Pike
Rockville, MD 20852

Response to Request for Information Regarding AREVA Inc. Topical Report ANP-10335P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation"

AREVA Inc. (AREVA) requested the NRC review and approval of Topical Report (TR) ANP-10335P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation" in Reference 1. The NRC provided a request for additional information (RAI) in Reference 2. AREVA's response to the RAI is enclosed with this letter. AREVA's response to previous RAIs regarding this topical report were transmitted to the NRC in References 3 and 4.

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

There are no commitments within this letter or its enclosures.

If you have any questions related to this information, please contact Mr. Morris E. Byram by telephone at (509) 375-8166, or by e-mail at Morris.Byram@areva.com.

Sincerely,

Gary Peters

Gary Peters, Director
Licensing & Regulatory Affairs
AREVA Inc.

cc: J. G. Rowley
Project 728

Ref. 1: Letter, Pedro Salas (AREVA) to Document Control Desk (NRC), "Request for Review and Approval of ANP-10335P Revision 0, 'ACE/ATRIUM 11 Critical Power Correlation'," NRC:15:012, February 27, 2015.

Ref. 2: Letter, Jonathan Rowley (NRC) to Gary Peters (AREVA), "Request for Additional Information Regarding AREVA Inc. Topical Report ANP-10335P/NP, Revision 0, 'ACE/ATRIUM 11 Critical Power Correlation' (TAC No. MF5841)," October 4, 2017.

Ref. 3: Letter, Gary Peters (AREVA) to Document Control Desk (NRC), "Revision to Supplemental Information Regarding Topical Report ANP-10335P Revision 0, 'ACE/ATRIUM 11 Critical Power Correlation'," NRC:17:016, March 30, 2017.

Ref. 4: Letter, Gary Peters (AREVA) to Document Control Desk (NRC), "Response to a Request for Additional Information Regarding Topical Report ANP-10335P, Revision 0, 'ACE/ATRIUM 11 Critical Power Correlation'," NRC:16:020, August 12, 2016.

Enclosures:

1. Proprietary copy of ANP-10335Q3P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation - RAIs"
2. Non-Proprietary copy of ANP-10335Q3NP, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation - RAIs"
3. Notarized Affidavit

AFFIDAVIT

STATE OF WASHINGTON)
) ss.
COUNTY OF BENTON)

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

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

3. I am familiar with the AREVA information contained in the report ANP-10335Q3P, Revision 0, entitled "ACE/ATRIUM 11 Critical Power Correlation - RAIs" referred to herein as "Document." Information contained in this document has been classified by AREVA as proprietary in accordance with the policies established by AREVA for the control and protection of proprietary and confidential information.

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

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

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

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

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

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

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

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

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

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

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

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

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

Morris E. Bazzard

SUBSCRIBED before me this 19th

day of October, 2017.

Hailey M. Siekawitch

HAILEY M SIEKAWITCH
Commission Expires
NOTARY PUBLIC
Sept. 28, 2020
STATE OF WASHINGTON

0414-12-F04 (Rev. 001, 03/10/2016)

AREVA

ACE/ATRIUM 11 Critical Power Correlation RAIs

ANP-10335Q3NP
Revision 0

Topical Report

October 2017

AREVA Inc.

Nature of Changes

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INTRODUCTION

The ACE/ATRIUM™* 11 Boiling Water Reactor (BWR) critical power correlation topical report was provided to the U.S. NRC for review in Reference 1. One additional request for additional information is addressed in this report.

---

* ATRIUM is a trademark of AREVA, Inc.

RAI-C:

Over the course of the review of Topical Report ANP-10335P, Revison 0, the NRC staff became aware of a leaking fuel rod at the Kernkraftwerk Leibstadt (KKL) nuclear power plant in Switzerland, a boiling water reactor/6 (BWR/6) plant operating on yearly cycles. The leaker was believed to have resulted from excessive cladding oxidation due to dryout. Subsequent inspections found widespread occurrences of dryout in locations throughout the core. In the next cycle, steps were taken to increase the minimum critical power ratio operating limit and prevent future instances of dryout. However, further inspections revealed even more dryout indications after the compensatory measures were taken. Additional inspections found that dryout had occurred in several cycles before the leaking fuel rod was identified.

The dryout indications were characterized by visible, wedge-shaped areas of increased oxidation on the fuel rods. The size, shape, and material properties of these areas of increased oxidation indicate that dryout occurred over an extended period of time while the reactor was operating at steady-state conditions, with cladding temperatures remaining below 800°C. Though the shape of the oxidized areas was consistent, the dimensions of the oxidized area and the oxide thickness varied. Dryout is believed to have occurred only when the reactor operated at greater than 95% of rated total core flow and was only observed in first-cycle bundles that had been operated with a fuel assembly power greater than 7.4 megawatts. Within these bundles, dryout indications were only found on certain symmetric rod positions and always in the upper part of the bundle.

Dryout of the type observed at the plant was not observed in critical power testing at similar bundle flow rates and powers. At no point during KKL's operation did the analytical methods developed by the fuel's vendor predict that margin to dryout would be sufficiently degraded for dryout to occur. Currently, the underlying mechanisms that caused the dryout at KKL are still unknown. Given this operating experience, how does AREVA provide reasonable assurance that adequate critical power margin will be maintained during normal operation, including the effects of anticipated operational occurrences?

AREVA Response C:

AREVA applies U.S. NRC reviewed and approved methods for the thermal limits. A summary description of the thermal limits methodology is provided in Reference 2. The thermal limits methodology, THERMEX, consists of a series of related analyses which establish an Operating Limit Minimum Critical Power Ratio (OLMCPR). The OLMCPR is determined from two calculated values, the Safety Limit Minimum Critical Power Ratio

(SLMCPR) and the limiting transient ΔCPR. The overall methodology is comprised of four major segments: 1) reactor core hydraulic methodology, 2) a critical power correlation, 3) plant transient simulation methodology, and 4) critical power safety limit methodology.

The first part, reactor core hydraulic methodology, provides pressure drop and flow distribution in the core and is described in References 2 and 3.

The second part is the critical power correlation that calculates the power or heat flux at the onset of dryout. These correlations are generally fuel design specific. Approved correlations include Reference 4 (ATRIUM-9B, ATRIUM-10 fuel), Reference 5 (ATRIUM-10 fuel), and Reference 6 (ATRIUM 10XM fuel). The critical power correlation for AREVA's newest fuel design, ATRIUM 11, (Reference 1) has been submitted for NRC review. AREVA also applies an NRC reviewed and approved methodology for co-resident fuel (Reference 7).

The third part, the plant transient simulation methodology is applied to calculate the ΔCPR. The methodology and computer codes for AREVA BWR plant transient analyses are the XCOBRA-T code (Reference 8) and the COTRANSA2 code (Reference 9). The COTRANSA2 code is used to calculate BWR system behavior for steady-state and transient conditions. This behavior is then used to provide input to the XCOBRA-T and XCOBRA codes, from which critical power ratios are determined for limiting transients. The regulatory review of AREVA's new transient methodology, AURORA-B (Reference 10) is in progress.

The fourth part provides the methodology for the safety limit calculation. The calculations supporting this part of the overall methodology are implemented in the SAFLIM2 code (Reference 11) and most recently the SAFLIM3D code (Reference 12).

The RAI specifically mentions critical power test programs. The critical power experimental test program of AREVA has been examined as part of the critical power correlation development program and has been audited by multiple NRC inspectors as part of the regulatory review process for the critical power correlations.

Reference 2 on page 3 concludes:

> *"The methodology described herein is based upon a series of assumptions which overestimate the potential of boiling transition and, as such, is judged to be conservative in the establishment of reactor operating thermal margins for boiling water reactors."*

The work of establishing thermal limits for nuclear reactors is in compliance with 10 CFR 50 App. B and the methods collectively provide assurance that the regulatory requirements on fuel clad integrity are completely satisfied.

Further evidence of the adequacy of the methods used by AREVA to establish appropriate thermal limits comes from AREVA's fuel inspection programs. [

]

* The ATRIUM 10XM fuel assemblies operated in KKL are [

].

Table 1. [ ]

[ ]

AREVA cannot compare AREVA fuel features, operation, or performance with that of the fuel which was found to be defective due to lack of knowledge of the failed fuel's design and the complete details of the investigation.

References

1. ANP-10335P, Revision 0, "ACE/ATRIUM 11 Critical Power Correlation," February 2015.

2. XN-NF-80-19(P)(A) Volume 3 Revision 2, "Exxon Nuclear Methodology for Boiling Water Reactors THERMEX: Thermal Limits Methodology Summary Description," January 1987.

3. XN-NF-79-59(P)(A), "Methodology for Calculation of Pressure Drop in BWR Fuel Assemblies," November 1983.

4. EMF-2209(P)(A), Revision 3, "SPCB Critical Power Correlation," September 2009.

5. ANP-10249P-A, Revision 2, "ACE/ATRIUM-10 Critical Power Correlation," March 2014.

6. ANP-10298P-A, Revision 1, "ACE/ATRIUM 10XM Critical Power Correlation," March 2014.

7. EMF-2245(P)(A), Revision 0, "Application of Siemens Power Corporation's Critical Power Correlations to Co-Resident Fuel," August 2000.

8. XN-NF-84-105(P)(A) Volume 1 and Volume 1 Supplements 1 and 2, "XCOBRA-T: A Computer Code for BWR Transient Thermal-Hydraulic Core Analysis," February 1987.

9. ANF-913(P)(A) Volume 1 Revision 1 and Volume 1 Supplements 2, 3, and 4, "COTRANSA2: A Computer Program for Boiling Water Reactor Transient Analyses," August 1990.

10. ANP-10300P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Transient and Accident Scenarios," December 2009.

11. ANF-524(P)(A) Revision 2 and Supplements 1 and 2, "ANF Critical Power Methodology for Boiling Water Reactors," November 1990.

12. ANP-10307P-A, Revision 0, "AREVA MCPR Safety Limit Methodology for Boiling Water Reactors," June 2011.

AREVA

ANP-10335NP
Revision 0

ACE/ATRIUM 11 Critical Power Correlation

Topical Report

February 2015

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Nomenclature

Acronym	**Definition**
ACE	AREVA Critical power Evaluator
AOO	Anticipated Operational Occurrence
BT	Boiling Transition
BWR	Boiling Water Reactor
CHF	Critical Heat Flux
CPR	Critical Power Ratio
ECPR	Experimental Critical Power Ratio defined to be the ratio of calculated to measured critical power
LOCA	Loss Of Coolant Accident
MCPR	Minimum Critical Power Ratio
PLR	Part Length Rod

1.0 INTRODUCTION

This document describes the ACE/ATRIUM™ 11*, AREVA Inc.'s critical power correlation for the boiling water reactor (BWR) ATRIUM 11 fuel design. This correlation is designed for application to steady-state design analysis, core monitoring, Anticipated Operational Occurrences (AOO's), transient accidents, LOCA, and instability analysis for the ATRIUM 11 fuel design. It may also be applied in the AREVA co-resident fuel methodology (Reference 9).

The first ACE critical power correlation was the ACE/ATRIUM 10 correlation (Reference 3), approved in August 2007. The correlation form was derived and the first application was to an existing fuel design, ATRIUM 10. The second application was the ACE/ATRIUM 10XM correlation (Reference 1), approved in March 2010. It used the same form of correlation as ACE/ATRIUM 10 but was applied to a different fuel design, ATRIUM 10XM.

The starting point for the ACE/ATRIUM 11 correlation is the ACE/ATRIUM 10XM correlation which is an NRC approved BWR critical power correlation for the ATRIUM 10XM fuel design (Reference 1). The ACE/ATRIUM 10XM correlation consists of a theoretical model that describes the point of maximal heat transfer in boiling, sometimes termed critical heat flux, boiling transition, commonly referred to as dryout. This theoretical model is constructed using **[**

]. The ACE/ATRIUM 10, ACE/ATRIUM 10XM, and the ACE/ATRIUM 11 correlations all share the same basic form of the correlation.

The differences in the two correlations arise from the physical differences between the ATRIUM 10XM and the ATRIUM 11 fuel bundle designs. The primary differences between the two bundle designs are the lattice size (11x11 versus 10x10), **[**

] and symmetric positioning of the central water canister. The ATRIUM 11 design also features an advanced fuel channel design. A more detailed description of the differences between the two bundle designs is provided in Section 4.0.

* ATRIUM is a trademark of AREVA Inc. registered in the United States and various other countries.

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 5.0. A complete description of the ATRIUM 11 database is provided in Section 8.0.

This topical report documents the ACE/ATRIUM 11 correlation. Sections are provided that describe regulatory applicability, comparison of ATRIUM 11 and ATRIUM 10XM data bases, ACE/ATRIUM 11 correlation evaluation model, applicability of ACE/ATRIUM 11 correlation to other fuel designs, statistical assessment and uncertainty analysis of ACE/ATRIUM 11 correlation with defining data set, the validation of the ACE/ATRIUM 11 correlation, assessment results, and quality assurance program.

2.0 SUMMARY

The ACE/ATRIUM 11 correlation can be used to accurately predict assembly critical power for the ATRIUM 11 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 Figure 6.11 for the ATRIUM 11 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 11 is adequately represented with a normal distribution using an overall mean of [ ]. The range of applicability for both ACE/ATRIUM 11 and ACE/ATRIUM 10XM are provided in Table 2.1.

2.1 *ACE/ATRIUM 11 Database*

The ACE/ATRIUM 11 database is comprised of [ ] steady-state data points taken on [ ] different test assemblies. The database was compiled from tests performed exclusively at the AREVA KATHY thermal hydraulic test facility located in Karlstein, Germany.

[ ] was followed in the development of this correlation. In accordance with the criteria set forth in this guideline, 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 11 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 11 database is described in more detail in Section 5.0, and additional detailed analysis of the test design, test strategy, radial peaking distributions, and axial power profiles are provided in Section 8.0 of this document.

2.2 *Comparison of the ACE/ATRIUM 11 Predictions to the Database*

The ACE/ATRIUM 11 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 11 is shown in Figure 2.1.

Table 2.1. Comparison of the Range of Applicability for the ATRIUM 11 and ATRIUM 10XM Correlations

[ ]

[ ]

Figure 2.1. Comparison of Calculated to Measured Critical Power Data for the ATRIUM 11 Fuel Design

3.0 REGULATORY REQUIREMENTS APPLICABLE TO THIS REPORT

In order to establish a licensing basis, licensees and vendors must analyze steady state, transient codes and methods in accordance with regulatory requirements such as those stated in NUREG-0800. NUREG-0800 is a document that embodies the U.S. Nuclear Regulatory Commission Standard Review Plan (SRP).

This topical report falls under the Standard Review Plan (SRP) Section 4.4 and associated criteria, titled "Thermal and Hydraulic Design."

SRP- Section 4.4, "Thermal and Hydraulic Design." 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 this report, 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.

4.0 COMPARISON OF ATRIUM 11 AND ATRIUM 10XM FUEL DESIGNS

Prior to proceeding with the description and evaluation of the ACE/ATRIUM 11 correlation model, a comparison is provided here (Sections 4.0 and 5.0), to highlight differences between the ATRIUM 10XM and ATRIUM 11 fuel designs, in particular those parts of the fuel assembly designs that lie within the heated length and their respective data bases. The ATRIUM 11 and the ATRIUM 10XM fuel designs share a common 3x3 water channel. This water channel is in the center of the ATRIUM 11 assembly (Figure 4.1) and offset from the center in the ATRIUM 10XM design (Figure 4.2). The ATRIUM 11 has [ ] fuel rod locations and the ATRIUM 10XM has [ ] fuel rod locations. The ATRIUM 10XM design also includes [ ] but this feature is not present in the ATRIUM 11. The axial features of the two test bundle designs can be compared in Figure 4.3.

Part length fuel rods are used on the design to optimize fuel distribution while maintaining hydraulic compatibility. The ATRIUM 11 fuel assembly design contains [ ]. The ATRIUM 10XM design contains [ ]. It is observed that [ ] are used in the ATRIUM 11 design and [ ] in the ATRIUM 10XM design. The [ ] may be compared in Figure 4.3.

Both fuel assembly designs include [ ]

[

]

The rod diameter of the ATRIUM 11 design (11x11 lattice) is [ ]. The ATRIUM 10XM rod diameter was 10.28 mm.

The ATRIUM 11 fuel channel [

] This feature does not exist on the ATRIUM 10XM fuel assembly design.

[ ]

Figure 4.1. ATRIUM 11 PLR Locations

[ ]

Figure 4.2. ATRIUM 10XM PLR Locations

[ ]

Figure 4.3. ATRIUM 11 / ATRIUM 10XM Test Assembly Comparison

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Figure 4.4. [ ]

Figure 4.5. [ ]

Figure 4.6. [ ]

Figure 4.7. [ ]

Figure 4.8. [ ]

5.0 COMPARISON OF ATRIUM 11 AND ATRIUM 10XM DATABASES

An in-depth statistical assessment of the database and associated uncertainties for the ATRIUM 11 fuel is provided in Sections 7.0 and 8.0 below. This section (Section 5), provides a brief comparison of the data bases of both the ATRIUM 10XM and the ATRIUM 11 fuel designs. This comparison is intended to point out the difference between the two fuel designs, but also and perhaps more importantly, the similarities in their thermal-hydraulic behavior. The ATRIUM 10XM fuel and its corresponding correlation are NRC approved, (Reference 1).

For both fuel types 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. The ATRIUM 11 database is compared to the ATRIUM 10XM database in Table 5.1. [

] A comparison of the range of data is provided in Table 5.2. Further discussion of the range of data is presented in defining the range of applicability in Section 6.13.

For an explicit ACE/ATRIUM 11 database assessment, refer to Section 8.0 below.

Table 5.1. Database Comparison

[ ]

Table 5.2. Range of Data for Each Correlation Development

[ ]

6.0 EVALUATION MODEL (EM)

6.1 *ACE/ATRIUM 11 Correlation Model Requirements and Description*

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 11 correlation, like its predecessors, the ACE/ATRIUM 10 correlation (Reference 3) and the ACE/ATRIUM 10XM correlation (Reference 1) is a correlation based on [ ]. A detailed step-by-step derivation of the ACE/ATRIUM 11 critical power correlation form is provided in Reference 3, Appendix A. The correlation is based on [ ]

[ ]

Table 6.1. [ ]

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6.2 [ ]

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6.3 [ ]

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6.4 *[ ]*

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Figure 6.1. [ ]

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Figure 6.2. [ ]

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Figure 6.3. [ ]

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Figure 6.4. [ ]

6.5 [ ]

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Figure 6.5. [ ]

Figure 6.6. [ ]

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Figure 6.7. [ ]

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Figure 6.8. [ ]

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Figure 6.9. [ ]

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6.8 [ ]

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Figure 6.10. [ ]

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6.10.1 [ ]

6.10.2 [ ]

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6.10.3 [ ]

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6.10.4 [ ]

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Figure 6.11. [ ]

6.11 [ ]

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Table 6.2. [ ]

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6.12 [ ]

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Figure 6.12. [ ]

Figure 6.13. [ ]

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Figure 6.14. [ ]

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Figure 6.15. [ ]

Figure 6.16. [ ]

Figure 6.17. [ ]

6.13 [ ]

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Figure 6.18. [ ]

6.13.2 [ ]

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6.13.3 [ ]

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6.13.4 [ ]

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Table 6.3. [ ]

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6.13.5 [ ]

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6.14 [ ]

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7.0 UNCERTAINTY ANALYSIS

7.1 *Assessment of ACE/ATRIUM 11 with Defining Data Set*

In this section the performance of the ACE/ATRIUM 11 critical power correlation is compared to the defining data set which consists of randomly selected [ ] of the total database. The following topics are presented here:

- ECPR trend plots comparing the critical power to the defining data set as a whole (Section 7.1.1).
- Statistical analysis by single variable subset, test subset, and in some cases two variable subsets of the defining data set (Section 7.1.2).

7.1.1 Overall Critical Power and ECPR Behavior (Defining)

The ACE/ATRIUM 11 correlation predictions are 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 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.

Figure 7.2 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 7.3. The data show no significant trends in pressure. Figure 7.4 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 7.5. There is no apparent trend with axial power shape. Figure 7.6 shows the ECPR as a function of K-factor. There is no apparent trend with K-factor.

[ ]

Figure 7.1. Calculated vs. Measured Critical Power (Defining)

[ ]

Figure 7.2. ECPR as Function of Mass Flow Rate (Defining)

Figure 7.3. ECPR as Function of Pressure (Defining)

Figure 7.4. ECPR as Function of Inlet Subcooling (Defining)

Figure 7.5. ECPR as Function of Axial Power Shape (Defining)

Figure 7.6. ECPR as Function of K-factor (Defining)

7.1.2 ACE/ATRIUM 11 Statistical Analysis of Defining Data Set

Overall statistics of the fit of the ACE/ATRIUM 11 correlation fit to the defining data set are provided in Table 7.1. The ECPR mean and ECPR standard deviation are in excellent agreement with the experimental data.

Higher moments for the ACE/ATRIUM 11 correlation analysis of ECPR are computed. Reference 10 provides the relationships for computing the higher order moments about the mean. The second moment about the mean is calculated

$$m_2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{7.1}$$

The third moment about the mean is calculated

$$m_3 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^3 \tag{7.2}$$

The fourth moment about the mean is calculated

$$m_4 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^4 \tag{7.3}$$

A measure of skewness is given by

$$\sqrt{\beta_1} = \frac{m_3}{m_2^{1.5}} \tag{7.4}$$

A measure of kurtosis is given by

$$\beta_2 = \frac{m_4}{m_2^2} \tag{7.5}$$

These statistics, computed for the ECPR from the ACE/ATRIUM 11 correlation, are summarized in Table 7.2. The distributional character of the ACE/ATRIUM 11 critical power ratios are shown in Figure 7.7 and Figure 7.8. Figure 7.7 is a histogram of the frequency of occurrence of ECPR while Figure 7.8 shows that the distribution [ ]

[

]

The number of degrees of freedom was estimated by the method of Satterthwaite (Reference 15) to be 145. The number of coefficients used to define the correlation (including 18 additive constants) is 46.

Table 7.1. Overall Statistics (Defining)

[ ]

Table 7.2. Higher Moments of ECPR Mean (Defining)

[ ]

Figure 7.7. Frequency Distribution of ECPR (Defining)

Figure 7.8. Expected Value for Normal Distribution of ECPR (Defining)

7.1.3 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 ECPR is examined as a function of binned mass flow rate in Table 7.3 for the defining data set. 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 seventh column shows the maximum value of the ECPR of the flow rate bin.
- The eighth column shows the number of data points in the flow rate bin that are above the ECPR 95/95 limit.
- The ninth column shows the percent of the data points in the flow rate bin that lie below the 95/95 limit.
- The tenth column shows the number of binned data points whose ECPR is above the 95/95 limit of the critical power correlation [

]

There is no trend in ECPR with mass flow rate. The standard deviation of ECPR also shows no trends with mass flow rate. [ ] shows that there are no significant numbers of within bin outliers for any of the bins. Examination of the distribution of ECPRs that are above the [ ] 95/95 limit show that they are distributed relatively evenly.

The ECPR is examined as a function of binned pressure in Table 7.4. There is no significant trend in ECPR. The standard deviation shows slightly higher standard deviations at higher pressure. [ ] shows that there are no significant numbers of within bin outliers at higher pressures. At higher pressures, a higher proportion of ECPRs above the [ ] 95/95 limit are observed. There are [ ] that include pressure variation, [ ]. Nearly all of the [ ] The other tests confirm that the ACE/ATRIUM 11 critical power correlation exhibits appropriate behavior with pressure. Consequently, these observations at higher pressures are considered insignificant.

The ECPR is examined as a function of binned inlet subcooling in Table 7.5. There is no significant trend in ECPR. The standard deviations are all comparable indicating no significant trend. [ ] shows that there are no significant numbers of outliers within any of the bins.

The ECPR is examined as a function of axial power shape in Table 7.6. There is no significant trend with ECPR. The standard deviation of the upskew and downskew shapes is comparable. [ ] shows that there are no significant numbers of within bin outliers for either upskew or downskew. A slightly higher proportion of ECPRs lie above the [ ] 95/95 limit with the upskew axial power shape.

The ECPR is examined as a function of K-factor in Table 7.7. The conclusion is that since there is no significant trend within the ECPR or standard deviation, the ACE/ATRIUM 11 correlation represents the data very well.

Table 7.3. Statistics by Binned Mass Flow Rate (Defining)

[ ]

Table 7.4. Statistics by Binned Pressure (Defining)

[ ]

Table 7.5. Statistics by Binned Inlet Subcooling (Defining)

[ ]

Table 7.6. Statistics by Axial Power Shape (Defining)

[ ]

Table 7.7. Statistics by Binned K-factor (Defining)

[ ]

7.1.4 Statistics by Test

The descriptive statistics for the overall data are examined by test in Table 7.8. The largest variation in ECPR mean of 1.0 is observed in test [ ], with an ECPR that is [ ]. All other values of ECPR are [ ]. The distribution of within test 95/95 outliers [ ] shows no significant anomalies.

The last column in Table 7.8 shows the number of data points in the defining data set whose ECPR is above the correlation 95/95 limit [ ]. It shows that most of the outliers are associated with [ ]. Based on the conclusions drawn in Section 7.1.3, it is concluded that these observations are not significant.

Table 7.8. Statistics by Test (Defining)

[ ]

7.1.5 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 7.9 provides statistics by subgroups of test and mass flow rate. Variations in the mean ECPR between bins is generally of lower magnitude than was observed with the ACE/ATRIUM 10XM correlation with respect to the paired variables mass flow rate and test peaking pattern. No significant trend is observed.

Table 7.10 provides statistics by subgroups of mass flow rate and pressure. [

]

Table 7.11 provides statistics by subgroups of mass flow rate and inlet subcooling. [

]

Table 7.12 provides statistics by subgroups of inlet subcooling and pressure. [

]

[

]

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 7.9. Statistics by Test and Mass Flow Rate

Table 7.9. Statistics by Test and Mass Flow Rate (cont.)

[ ]

Table 7.10. Statistics by Mass Flow Rate and Pressure (Defining)

[ ]

Table 7.11. Statistics by Mass Flow Rate and Inlet Subcooling (Defining)

[ ]

Table 7.12. Statistics by Inlet Subcooling and Pressure (Defining)

[ ]

7.2 *ACE/ATRIUM 11 Correlation Validation*

The development of the ACE/ATRIUM 11 correlation required that the database be divided into two sets, one for correlation development (randomly selected [ ] of the total data collected) and the other for correlation validation ([ ] of the total data collected). 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 11 critical power correlation.

The ACE/ATRIUM 11 critical power correlation was further validated by comparing its prediction with transient critical power measurements.

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 7.2.1).
- ECPR trend plots comparing the critical power to the validating data set as a whole (Section 7.2.2).
- Statistical analysis by single variable subsets (Section 7.2.3).
- Distribution of additive constant residual (Section 7.2.4).
- Correlation behavior with [ ]
- ACE/ATRIUM 11 critical power correlation benchmark to transient test data (Section 7.3).

7.2.1 Overall Statistical Performance

The overall statistics of the correlation are presented in Table 7.13.

Table 7.13. Overall Statistics Comparison

[ ]

The standard deviation of the validating data set is slightly higher than the defining data set but the mean ECPR of the validating data set is slightly lower than the mean ECPR of the defining data set. The differences are insignificant. On the basis of these statistics, the ACE/ATRIUM 11 critical power correlation is in excellent agreement with the validating data set and with the combined data set.

7.2.2 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 7.9. 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 7.10. 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 significant trends exist.

The ECPR as a function of pressure is shown in Figure 7.11. A trend line representing a linear least square fit of the ECPR with pressure is shown on the plot confirming that no significant trends exist.

The ECPR as a function of inlet subcooling is shown in Figure 7.12. 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 with inlet subcooling exist.

The ECPR as a function of axial power shape is shown in Figure 7.13. There is no significant trend with axial power shape.

The ECPR as a function of K-factor is shown in Figure 7.14. There is no significant trend with K-factor.

On the basis of the observed trends in the validating data set, the ACE/ATRIUM 11 critical power correlation is in excellent agreement with the experimental data and exhibits no significant trends.

Figure 7.9. Calculated vs. Measured Critical Power (Validating)

Figure 7.10. ECPR as Function of Mass Flow Rate (Validating)

Figure 7.11. ECPR as Function of Pressure (Validating)

Figure 7.12. ECPR as Function of Inlet Subcooling (Validating)

Figure 7.13. ECPR as Function of Axial Power Shape (Validating)

Figure 7.14. ECPR as Function of K-factor (Validating)

7.2.3 Statistical Analysis

The frequency distribution of ECPR for the validating data set is shown in Figure 7.15. [

]

The validating data set is binned by mass flow rate in Table 7.13. There is no trend in ECPR with mass flow rate. The standard deviation of ECPR is comparable for all of the bins. [

] The number of data points whose ECPR is above the [ ] 95/95 limit shows no significant trends.

The validating data set is binned by pressure in Table 7.14. There is no significant trend in ECPR. The standard deviation is somewhat higher at higher pressures. [

]

The validating data set is binned by inlet subcooling in Table 7.16. If bins with more than 5 data points are considered, there is no significant trend in ECPR. The standard deviation of the bins with more than 5 data points are all comparable. [

]

Similar statistical examinations are performed for the axial power shape, in Table 7.17. There is no significant trend with ECPR. The standard deviation of [

] is comparable. [

]

The conclusion is that there is no significant trend with axial power shape.

The ECPR is binned as a function of K-factor in Table 7.18. No significant trends are observed in the ECPR or ECPR standard deviation.

The results by test are examined in Table 7.19. [

]

The conclusion is that the validating data set, as a whole, by important variables, and by individual test, confirm the applicability of the ACE/ATRIUM 11 critical power correlation to the population.

Table 7.14. ECPR Binned by Mass Flow Rate (Validating)

[ ]

Table 7.15. ECPR Binned by Pressure (Validating)

[ ]

Table 7.16. ECPR Binned by Inlet Subcooling (Validating)

Table 7.17. ECPR Binned by Axial Power Shape (Validating)

Table 7.18. ECPR Binned by K-factor (Validating)

[ ]

Table 7.19. Statistics by Test (Validating)

[ ]

Figure 7.15. Frequency Distribution of ECPR (Validating)

Figure 7.16. Expected Value for Normal Distribution of ECPR (Validating)

7.2.4 Additive Constant Residual

A residual additive constant for each state point can be obtained by subtracting the final additive constant from the experimental additive constant of the limiting rod of each data point. A frequency plot of these residuals in additive constant for the combined data set is provided in Figure 7.17. [ ]

[ ]

Figure 7.17. Distribution of Additive Constant Residuals (Combined)

7.2.5 [ ]

[

] Therefore, the critical power correlation is valid for all inlet subcooling as described in the range of applicability, Table 2.1.

7.3 *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 11 when using the ACE/ATRIUM 11 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 7.18 shows the forcing function

characteristics for a typical LRNB test and Figure 7.19 shows the comparable forcing function characteristics for a typical loss of flow event.

A total of [ ] ATRIUM 11 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. Of these [ ] transient critical power tests, [

] Table 7.20 summarizes initial state conditions for all the transient tests.

The AREVA transient thermal hydraulic code XCOBRA-T (References 13 and 14), was used to predict the transient test results using the ACE/ATRIUM 11 critical power correlation. The test power forcing function provides the boundary condition of power, which is modeled in XCOBRA-T [

]

The results are summarized in Table 7.21. [

]

[

]

Table 7.20. Transient Initial Conditions

[ ]

Table 7.20. Transient Initial Conditions (continued)

[ ]

Table 7.20. Transient Initial Conditions (continued)

Table 7.21. XCOBRA-T ATRIUM 11 Transient Dryout Results

Table 7.21. XCOBRA-T ATRIUM 11 Transient Dryout Results (continued)

Table 7.21. XCOBRA-T ATRIUM 11 Transient Dryout Results (continued)

Table 7.22. XCOBRA-T K-Factor Iteration Results

[ ]

Figure 7.18. Typical LRNB Transient Forcing Function

Figure 7.19. Typical Loss of Flow Transient Forcing Function

8.0 ACE/ATRIUM 11 MODEL AND DATABASE ASSESSMENT RESULTS

The ACE/ATRIUM 11 database contains [ ] validate the correlation. All data were taken at the AREVA KATHY thermal hydraulic test facility located in Karlstein, Germany.

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 power distribution is decomposed into two parts: a normalized axial power shape, and normalized radial (local) peaking factors. The axial power shape will be described in Section 8.1.2 below.

The usual practice is for the local peaking of the test rods to vary between [ ]. 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 11 has one-eighth symmetry. Figure 8.1 shows all the peaked locations and the tests in which they were peaked. All full length rod locations within the bundle were peaked, achieved dryout, or can be covered via symmetry considerations. In addition, [ ].

8.1.2 Axial Power Profile

[ ]

[ ]. Table 8.1 summarizes the axial power shape and number of data points in each test series.

The test rod axial power shapes are shown in [ ]. 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 above the peak of an axial power profile (downstream). [ ].

Table 8.1. Dryout Test Data

[ ]

Figure 8.1. ATRIUM 11 Tests By Peaked Rod Position

[ ]

Figure 8.2. [ ]

[ ]

Figure 8.3. [ ]

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 onset of dryout is observed. 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 11 Data*

Table 8.2 contains the measured and calculated critical power ratio of the combined data sets. The test and run number are identified for each data point, along with the pressure, inlet subcooling, and mass flow rate. The measured critical power is shown along with the ECPR (ratio of calculated to measured critical power). The measured axial location of onset of dryout is shown in meters from the beginning of heated length, along with the calculated onset of dryout location.

[ ] present the dryout test peaking patterns and their associated critical power versus inlet subcooling plots for both the test data and the ACE/ATRIUM 11 correlation predictions. [

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Table 8.2. ACE/ATRIUM 11 Data and Analysis Results

Table 8.2. ACE/ATRIUM 11 Data and Analysis Results (continued)

Table 8.2. ACE/ATRIUM 11 Data and Analysis Results (continued)

[ ]

Table 8.2. ACE/ATRIUM 11 Data and Analysis Results (continued)

Table 8.2. ACE/ATRIUM 11 Data and Analysis Results (continued)

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Table 8.2. ACE/ATRIUM 11 Data and Analysis Results (continued)

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Table 8.2. ACE/ATRIUM 11 Data and Analysis Results (continued)

Table 8.2. ACE/ATRIUM 11 Data and Analysis Results (continued)

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Table 8.2. ACE/ATRIUM 11 Data and Analysis Results (continued)

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Table 8.2. ACE/ATRIUM 11 Data and Analysis Results (continued)

Table 8.2. ACE/ATRIUM 11 Data and Analysis Results (continued)

Table 8.2. ACE/ATRIUM 11 Data and Analysis Results (continued)

Figure 8.4. [ ]

Figure 8.5. [ ]

[ ]

Figure 8.6. [ ]

[ ]

Figure 8.7. [ ]

Figure 8.8. [ ]

Figure 8.9. [ ]

Figure 8.10. [ ]

Figure 8.11. [ ]

Figure 8.12. [ ]

Figure 8.13. [ ]

Figure 8.14. [ ]

Figure 8.15. [ ]

[ ]

Figure 8.16. [ ]

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Figure 8.17. [ ]

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Figure 8.18. [ ]

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Figure 8.19. [ ]

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Figure 8.20. [ ]

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Figure 8.21. [ ]

Figure 8.22. [ ]

Figure 8.23. [ ]

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Figure 8.24. [ ]

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Figure 8.25. [ ]

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Figure 8.26. [ ]

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Figure 8.27. [ ]

Figure 8.28. [ ]

Figure 8.29. [ ]

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Figure 8.30. [ ]

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Figure 8.31. [ ]

Figure 8.32. [ ]

Figure 8.33. [ ]

Figure 8.34. [ ]

Figure 8.35. [ ]

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Figure 8.36. [ ]

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Figure 8.37. [ ]

Figure 8.38. [ ]

Figure 8.39. [ ]

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Figure 8.40. [ ]

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Figure 8.41. [ ]

Figure 8.42. [ ]

Figure 8.43. [ ]

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Figure 8.44. [ ]

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Figure 8.45. [ ]

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Figure 8.46. [ ]

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Figure 8.47. [ ]

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Figure 8.48. [ ]

[ ]

Figure 8.49. [ ]

[ ]

Figure 8.50. [ ]

Figure 8.51. [ ]

Figure 8.52. [ ]

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. The inner water canister is simulated in the tested assembly in that it preserves the correct external dimensions but contains no flow.

From the perspective of critical power, the geometry of the assembly between the beginning and end of the heated length is reproduced. In both the production design and the tested assembly, the rod diameter is [ ]. The pitch between rods is the same in both production and test assemblies.

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. An unheated short section at the top of the part length rod simulates the unheated plenum in the top of the production assembly part length rods. [

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[

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10.0 QUALITY ASSURANCE PROGRAM (QAP)

10.1 *QAP Specific to Correlation Development*

The assessment results of Section 8.0 demonstrates that the evaluation model (namely the ACE/ATRIUM 11 Correlation) is maintained under a quality assurance program that meets the regulatory requirements of 10 CFR Part 50.

The AREVA quality assurance program covers the procedures for design control, document control, software configuration control and testing, and error identification and corrective actions are used in the development and maintenance of the correlation evaluation model, as well as in the correlation assessment, and the uncertainty analysis. Additionally, the AREVA staff determined that the documents were accurate, complete, and consistent with all symbols and nomenclature being defined and consistently used. The (QAP) program also ensures adequate training of personnel involved with code development and maintenance, as well as those who perform the analyses.

10.2 *QAP Specific to ACE/ATRIUM 11 Testing*

The testing organization (that operates the KATHY loop) is treated as a supplier for testing and data that is subject to 10 CFR Part 50 Appendix B. As such, periodic audits are performed on the quality assurance program of the supplier to ensure that it remains in compliance with the quality assurance requirements. The frequency of the audits is based on the compliance history of the supplier and the frequency of use of the supplier. Test specifications are provided to the quality organization to ensure they are informed of the use of the supplier. Certification of the supplier is provided for a specified period of time. By procedure, test specifications for this supplier are not issued unless the supplier is certified.

The U.S. NRC conducted an audit of the ATRIUM 11 test program between January 13 and January 16, 2014. The topics of this audit included site and personal safety requirements, data collection process, description of the ATRIUM 11 fuel assembly hardware, data collection procedures, observation of quality assurance procedures during testing, fuel assembly fabrication, and discussion of the quality assurance program. Experimental planning and correlation development were also discussed during this audit.

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6. [ ]

7. [ ]

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Appendix A List of Symbols

Symbol	Description	Units

[ ]

Symbol	Description	Units

Symbol	Description	Units

Symbol	Description	Units

Symbol	Description	Units

Identification of Modifications to ANP-10335NP-000

Item	Section(s) or Page(s)
1	Page 2-3
2	Page 7-2
3	Page 7-23

[ ]

Figure 2.1. Comparison of Calculated to Measured Critical Power Data for the ATRIUM 11 Fuel Design

Figure 7.1. Calculated vs. Measured Critical Power (Defining)

Figure 7.2. ECPR as Function of Mass Flow Rate (Defining)

Figure 7.9. Calculated vs. Measured Critical Power (Validating)

Figure 7.10. ECPR as Function of Mass Flow Rate (Validating)