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.

<u>Transient Testing</u>

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.

Transient Applications

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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Principal Contributor: Reed Anzalone, NRR/DSS/SNPB

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