FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT ANP-10298PA, REVISION 0, SUPPLEMENT 1P, REVISION 0,

"IMPROVED K-FACTOR MODEL FOR ACE/ATRIUM 10XM CRITICAL

POWER CORRELATION"

AREVA NP INC.

TAC NO. ME7963

1.0 INTRODUCTION AND BACKGROUND

By letter dated December 21, 2011, AREVA NP Inc. (AREVA) submitted to U.S. Nuclear Regulatory Commission (NRC) staff for review and approval for referencing in licensing action Topical Report (TR) ANP-10298PA, Revision 0, Supplement 1P, Revision 0, "Improved K-factor Model for ACE/ATRIUM 10XM Critical Power Correlation" (Reference 1). This TR documents a revision to the Critical Power Ratio (CPR) correlation for ATRIUM 10XM fuel for Boiling Water Reactors (BWRs). The significant change in the Supplement 1P document, relative to ANP-10298PA, Revision 0 (Reference 3), is a revision in the K-factor methodology used to determine the additive constants for the CPR correlation. The K-factor methodology was revised in response to deficiencies in the axial averaging process.

The K-factor is a modeling parameter that characterizes the effect on CPR of radial fuel rod peaking distribution within an assembly. The critical power varies inversely with the K-factor, i.e., as K-factor increases in value the critical power decreases in value. The K-factor has two parts; the first part depends solely on the rod peaking factors of the specific rod and its neighbors and the second part named an additive constant accounts for other effects such as spacing and geometry determined from experimental data. This CPR correlation is applicable to steady-state design and analysis, core monitoring, anticipated operational occurrences (AOOs), accidents, loss-of-coolant accidents (LOCA), and instability analysis for the ATRIUM 10XM fuel design.

Pacific Northwest National Laboratory (PNNL) has acted as a consultant to the NRC in this review. PNNL evaluated this TR using the criteria and guidance provided in NUREG-0800, "Standard Review Plan" (SRP), Sections 4.4, "Thermal and Hydraulic Design" and SRP Chapter 15, "Transients and Accident Analyses." Supplement 1 to the TR was evaluated.

2.0 REGULATORY EVALUATION

The NRC staff used the guidance of SRP, NUREG-0800, Section 4.4, "Thermal and Hydraulic Design," for the review of ANP-10298PA, Revision 0, Supplement 1P, Revision 0. SRP Section 4.4 acceptance criteria are based on meeting the requirements of General Design Criteria (GDC) 10 and GDC 12 of Appendix A to Title 10 of the *Code of Federal Regulations* Part 50.

GDC 10 states: *The reactor core and associated coolant, control, and protection systems shall be designed with the appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences.*

GDC 12 states: *The reactor core and associated coolant, control, and protection systems shall be designed to assure that power oscillations which can result in conditions exceeding specified acceptable fuel design limits are not possible or can be reliably and readily detected and suppressed.*

GDC 10 requires proper thermal-hydraulic design of the reactor core and associated systems necessary to assure that sufficient margin exists with regard to maintaining adequate heat transfer from the fuel to the reactor cooling system (RCS). Failure to maintain sufficient margin can result in a transition from nucleate boiling to film boiling on the fuel cladding surface which decreases the heat transfer coefficient at the clad surface and the surface temperature rises significantly, eventually leading to fuel failure and the release of fission products to the RCS.

GDC 12 requires that the reactor core and associated coolant, control, and protection systems be designed to assure that power oscillations that result in conditions exceeding specified acceptable fuel design limits are not possible or can be reliably and readily detected and suppressed. Compliance with GDC 12 provides assurance that the thermal-hydraulic design of the reactor core and associated systems protect the reactor from the consequences of power oscillations that could challenge the integrity of the fuel and result in the release of fission products.

The K-factor methodology in the original ACE correlation for ATRIUM 10XM fuel design (Reference 3) was revised to rectify the deficiencies in the axial averaging process. The additive constants were updated during the K-factor methodology update. Evaluations performed by AREVA have confirmed that the original ACE/ATRIUM 10XM Critical Power Correlation (CPC) did not require revision as a result of the K-factor update. The range of applicability of the CPC remains unchanged.

The NRC staff has found that the ACE/ATRIUM correlation as improved by Reference 2 is acceptable to predict critical power and its limiting (minimum) value should be established so that at least 99.9 percent of the fuel rods in the core will not be expected to experience Boiling Transition (BT) during normal operation or AOOs.

3.0 TECHNICAL EVALUATION

In Supplement 1P, Revision 0, the K-factor methodology is revised to address deficiencies identified in an AREVA Condition Report (Reference 4) regarding the calculation of the K-factor within the ACE/ATRIUM-10 and ATRIUM 10XM CPR correlations (References 2 and 7). These deficiencies were shown to have influenced the predicted results in a non-conservative manner for this CPR correlation, for fuel assemblies with downskew axial power shape. Initial evaluations performed on existing fuel cycle designs that use the ACE correlation concluded that this deficiency has no significant impact for ATRIUM 10XM fuel designs.

The technical issues of this review exactly paralleled those of the review of Supplement 1P to ANP-10249PA, "Improved K-factor Model for ACE/ATRIUM-10 Critical Power Correlation," (Reference 7). A plant specific application of the improved K-factor model for ATRIUM 10XM fuel design was previously approved for Brunswick Steam Electric Plant (BSEP) Units 1 and 2. (References 5, 8, and 9)

3.1 Improved K-factor Model

As documented in the submitted TR, the ACE/ATRIUM 10XM CPR correlation is unchanged from the formulation in ANP-10298PA, Revision 1, which was reviewed and approved in 2010, except for one small modification. This change is in the definition of the radial peaking function used to calculate the assembly K-factor. The main purpose of the radial peaking function is to capture the effect on critical power of the radial power distribution. It is also sensitive to effects of lattice geometry and spacer grid design, due to their effect on the two-phase flow distribution in the assembly subchannels. This function includes the additive constants associated with each rod location in the lattice, and captures the local thermal-hydraulic behavior within the fuel assembly by means of statistical fitting to the experimental data constituting the correlation's database.

The assembly K-factor is determined from local k-factors calculated for each rod in the assembly, based on local rod power. In the original formulation (see ANP-10249PA, Revision 1), the local rod k-factor was calculated as an axial average, by integrating over the heated length of the rod. This approach was intended as a means of capturing the total effect of individual rod power on critical heat flux behavior in the assembly, including the effect of axial variation in individual rod power distribution. However, the integration introduces a subtle bias into the local rod k-factor values, with the implicit non-physical assumption that downstream conditions as well as upstream conditions affect local dryout behavior. In actual application, however, it was shown that this effect was a concern only for conditions with downskew power distribution (see AREVA Condition Report, 2010-7210-FA Engineering Condition (Reference 4)).

The correction for this deficiency, as documented in Supplement 1 (Reference 2) was to re-formulate the dryout power model to calculate the local radial peaking term as a function of axial location, rather than integrating to obtain an axial average value. Equation 3.1 of Reference 2 is solved for the margin to dryout at each location and the power is adjusted until the node with minimum margin is at dryout. This means that the margin at each axial node is based on the integration of the equation up to the node, i.e., the solution at the limiting node is independent of the conditions in the node above the limiting node (dryout node). Use of the

local conditions rather than the axial average results in a definition of the local rod k-factor that more accurately captures the effect of axial power distribution on dryout behavior. However, the effect is significant only with downskew power shapes. For cosine and upskew shapes, the integration does not introduce a discernible difference in the predicted dryout behavior, since the averaged value is quite close to the local value for the typical dryout location with these power shapes. For downskew power shapes, the dryout location is typically much lower down, and the axial averaged value can differ significantly from the local value.

3.2 Calculation of Additive Constants

The critical power behavior of the individual fuel rods within the fuel bundle is influenced by the spacers and the bundle geometry. Additive constants are factors that distinguish the critical power performance of each rod and they are position dependent. They are considered as a flow/enthalpy redistribution characteristic for a given bundle and spacer design. All other components of the model were unchanged, but the axial resolution of the model was increased to more accurately capture the shape of the axial power distribution for each rod in the assembly. With these revisions implemented, the additive constants were re-derived, using the same procedure documented originally in ANP-10298PA, Revision 0. All other empirical coefficients of the ACE/ATRIUM 10XM CPR correlation were unchanged in this procedure, which generated a new set of additive constants for use with this correlation in applications to reactor analyses. Estimation of initial additive constants for full length and part-length rods as well as the iteration scheme for the determination of final additive constants are discussed in detail in Sections 3.3.1 through 3.3.4 of Reference 2. The observed changes in additive constants are generally small (Figure 3-5 of Reference 2) and consistent with the improved K-factor methodology implementation.

Additive constant uncertainty was recalculated per procedure discussed in Section 3.4 of Reference 2. The improved K-factor methodology has caused to decrease the overall additive constant uncertainty by 2.1 percent from Reference 3.

Additive constant uncertainty for high peaking rods was calculated as an additional incremental uncertainty from a statistical distribution of the respective additive constant uncertainties. A detailed process for the additional incremental uncertainty is described in Section 3.3 of the SE.

Overall, the effect of the new additive constants on the correlation predictions is extremely small. The mean Experimental Critical Power Ratio (ECPR) which is ratio of calculated to the measured critical power, for the correlation with this correction is **[ ]**, with a standard deviation of **[ ]**, compared to an ECPR of **[ ]** and standard deviation of **[ ]**, with the axially averaged K-factor. The fit of the correlation to its database is essentially the same, due to using the same statistical fitting methodology and criteria as was used originally. The NRC staff finds the methodology for calculating the additive constants acceptable.

3.3 Additive Constants for Controlled Assemblies with Higher Peaking Factor

Additive constant uncertainty for high peaking rods was calculated as an additional incremental uncertainty from a statistical distribution of the respective additive constant uncertainties. Table 3-1 of Reference 2 lists the incremental uncertainty for high peaked rods and the additive constant uncertainty for high peaked rods to be used in the safety limit analysis.

The basis for the additional uncertainty to be applied for assemblies when local peaking exceeds **[ ]** had been agreed upon and accepted by NRC staff (References 12 and 13). The SE for Reference 12 provides the clarification,

> *Although local peaking factors may be exceeded in controlled bundles, these bundles by definition are not limiting bundles; consequently, they do not factor in the calculation of the minimum critical power ratio (MCPR) safety limit. If, however, in the process of calculating the MCPR safety limit, the local peaking factor of* ***[ ]*** *is exceeded, an additional additive constant uncertainty is applied on a rod-by-rod basis in accordance with Table 3.15 of Reference 12.*

This condition has been extended to the treatment of additive constants for ACE/ATRIUM 10XM correlation and the additional uncertainty is listed in Table 3-1 of Reference 2 for high peaked rods. This is acceptable to the NRC staff.

3.4 Transient Benchmarking

Transient dryout tests were performed to confirm the fact that steady-state dryout correlations are conservative for use in BWR transient methodology for the ATRIUM 10XM fuel design when using the ACE/ATRIUM 10XM CPC. The limiting transient test for benchmarking was the simulated Load Rejection without bypass events that consist of power and pressure ramps and flow decay and the simulated loss of flow events that consist of flow decay and power decay. Transient critical power tests were repeated using the revised K-factor methodology.

The results obtained with the improved formulation in benchmarking to transient CPR data, as documented by AREVA, show essentially identical behavior to that reported for the original formulation of the correlation. In addition, the evaluations for the BSEP show no significant changes in operational limits or Technical Specifications.

3.5 Application of ACE/ATRIUM 10XM to Co-resident Fuel

ANP-10298PA (Reference 2, Section 5.14) states that the ACE/ATRIUM 10XM CPC may also applicable to other vendor fuel designs (Reference 10). However, the application of ACE/ATRIUM 10XM correlation for other vendor fuel or future AREVA NP fuel designs with different critical power performance requires assessment, determination of uncertainties, and the determination of boundaries. References 10 and 11 list the necessary steps for the application of approved AREVA critical power correlations to various co-resident fuel designs that were previously exposed in reactors. The process and methodology for evaluating the critical power performance of both resident and co-resident fuel consist of either an indirect or direct evaluation process. The indirect process is used when the co-resident fuel critical power correlation is available but the experimental critical power data for the co-resident fuel is not. The direct process is used when the experimental critical power data for the co-resident fuel are available.

The indirect and direct processes for the application of AREVA critical power correlations to various co-resident fuel designs are detailed in Section 3.0 of Reference 10.

4.0 CONCLUSION

The deficiencies in the ACE/ATRIUM 10XM CPR correlation that are corrected with the changes introduced in the formulation for the K-factor, and corresponding minor adjustments in the procedure for the derivation of the additive constants, represent a small but locally discernible improvement in the correlation, particularly for application to conditions with downskew power distributions. The overall effect of the changes documented in the TR submitted for review is to introduce more physically realistic modeling of the local subchannel hydrodynamics that influence dryout behavior in a fuel rod array.

The proposed corrections are acceptable improvements in the dryout modeling approach used in the ACE/ATRIUM 10XM CPR correlation.

The NRC staff acknowledges that AREVA intends to incorporate ANP-10298PA, Revision 0, Supplement 1P, Revision 0, information into the previously accepted TR ANP-10298PA, Revision 0, "ACE/ATRIUM 10XM Critical Power Correlation," dated March 2010 to create Revision 1 of the accepted TR. Therefore, Revision 1 of TR ANP-10298PA can be submitted as the accepted version of the TR.

5.0 LIMITATIONS AND CONDITIONS

1. The ACE/ATRIUM 10XM methodology may only be used to perform evaluations of AREVA ATRIUM 10XM fuel design. The ACE/ATRIUM 10XM correlation may also be used to evaluate the performance of the co-resident fuel in mixed cores as discussed in Section 3.4 of this SE.

2. ACE/ATRIUM 10XM correlation shall not be used outside the range of applicability defined by the range of the test data prescribed in Table 2.1 of Reference 2.

6.0 REFERENCES

1. Letter NRC:11:122 from Pedro Salas (AREVA NP Inc.) to US NRC, "Request for Review and Approval of ANP-10298PA, Revision 0, Supplement 1P, Revision 0, "Improved K-factor Model for ACE/ATRIUM 10XM Critical Power Correlation," AREVA NP, December 21, 2011 (Agencywide Documents Access and Management System (ADAMS) Accession Number ML11363A121).

2. ANP-10298PA, Revision 0, Supplement 1P, Revision 0, "Improved K-factor Model for ACE/ATRIUM 10XM Critical Power Correlation," AREVA NP, December 2011 (ADAMS Accession Number ML113630324).

3. ANP-10298PA, Revision 0, "ACE/ATRIUM 10XM Critical Power Correlation," AREVA NP Inc., March 2010 (ADAMS Accession Number ML101190042).

4. Letter BSEP 11-0040 from Michael J. Annacone (BSEP) to US NRC, "Additional Information Supporting License Amendment Request to Add Analytical Methodology ANP-10298PA to Technical Specification 5.6.5, Core Operating Limits Report (COLR),"

Progress energy, April 6, 2011. (Enclosures: AREVA Operability Assessments CR 2011-2274 and CR 2010-7210) (ADAMS Accession Number ML111020442).

5. ANP-3086(P), Revision 0, Brunswick Unit 1 and Unit 2 SLMCPR Operability Assessment Critical Power Correlation for ATRIUM 10XM Fuel – Improved K-factor Model, February 2012 (ADAMS Accession Number ML120760256).

6. Letter BSEP 12-0104 from Michael J. Annacone (BSEP) to US NRC, “Response to Request for Additional Information Regarding License Amendment Request for Addition of Analytical Methodology Topical Report to Technical Specification 5.6.5, "CORE OPERATING LIMITS REPORT (COLR)," and Revision to Technical Specification 2.1.1.2 Minimum Critical Power Ratio Safety Limit, Duke Energy, September 21, 2012 (ADAMS Accession Number ML122770484).

7. ANP-10249PA, Revision 1, Supplement 1P, Revision 0, “Improved K-factor Model for ACE/ATRIUM 10 Critical Power Correlation,” AREVA NP, Inc., December 2011 (ADAMS Accession Number ML113630109).

8. Letter BSEP 12-0031 from Michael J. Annacone (BSEP) to US NRC, “Request for License Amendments - Addition of Analytical Methodology Request for License Amendments - Addition of Analytical Methodology Topical Report to Technical Specification 5.6.5, "CORE OPERATING LIMITS REPORT (COLR)" and Revision to Technical Specification 2.1.1.2 Minimum Critical Power Ratio Safety Limit,” Progress Energy, March 6, 2012 (ADAMS Accession Number ML120760256).

9. Letter from US NRC to Michael J. Annacone (BSEP), “Brunswick Steam Electric Plant, Units 1 and 2, Draft Safety Evaluation for Amendments Regarding Addition of Analytical Methodology Topical Reports to Technical Specification 5.6.5 and Revision to Minimum Critical Power Ratio Safety Limit (TAC Nos. ME8135 and ME8136),” US NRC, February 11, 2013.

10. EMF-2245(P)(A), Revision 0, “Application of Siemens Power Corporation’s Critical Power Correlations to the Co-Resident Fuel,” Siemens Power Corporation, August 2000 (ADAMS Accession Number ML031290413).

11. EMF-1125(P)(A) Supplement 1, Appendix C, “ANFB Critical Power Correlation Application for Co-resident Fuel,” Siemens Power Corporation, May 1997.

12. EMF-2209(P)(A), Revision 1, “SPCB Critical Power Correlation,” Siemens Power Corporation, July 2000 (ADAMS Accession Number ML031290413).

13. Letter from J. F. Mallay (Siemens) to US NRC, “SER Conditions for EMF-2209(P), Revision 1, SPCB Critical Power Correlation,” April 20, 2000 (ADAMS Accession Number ML003708323).

Attachment 1: Resolution of Comments (Non-Proprietary)

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