ATTACHMENT 9

Browns Ferry Nuclear Plant (BFN)
Units 1, 2, and 3

Technical Specifications (TS) Change 478

Addition of Analytical Methodologies to Technical Specification 5.6.5.b for Browns Ferry 1, 2, & 3, and Revision of Technical Specification 2.1.1.2 for Browns Ferry Unit 2, in Support of ATRIUM-10 XM Fuel Use at Browns Ferry

Thermal Hydraulic Design Report

Attached is the non proprietary version of the thermal hydraulic design report.

ANP-3082(NP)
Revision 1

Browns Ferry Thermal-Hydraulic Design Report for ATRIUM™ 10XM Fuel Assemblies

August 2012

AREVA

AREVA NP Inc.

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ANP-3082(NP)
Revision 1

Browns Ferry Thermal-Hydraulic Design Report for ATRIUM™ 10XM Fuel Assemblies

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Nature of Changes

Item	Page	Description and Justification
1.	None	The nonproprietary version was revised because of a typographic error in the header. No changes have been made to the proprietary version.

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Nomenclature

AOO	anticipated operational occurrences
ASME	American Society of Mechanical Engineers
BWR	boiling water reactor
BWROG	BWR Owners Group
CHF	critical heat flux
CLTP	current licensed thermal power
CPR	critical power ratio
CRDA	control rod drop accident
ECCS	emergency core cooling system
IFG	improved FUELGUARD
LOCA	loss-of-coolant accident
LTP	lower tie plate
MAPLHGR	maximum average planar linear heat generation rate
MCPR	minimum critical power ratio
MWR	metal-water reaction
NRC	Nuclear Regulatory Commission, U.S.
OLMCPR	operating limit minimum critical power ratio
OPRM	oscillation power range monitor
PCT	peak cladding temperature
RPF	radial peaking factor
SER	safety evaluation report
SFG	standard FUELGUARD
SLMCPR	safety limit minimum critical power ratio
UO_2	uranium dioxide
UTP	upper tie plate

1.0 Introduction

The results of Browns Ferry thermal-hydraulic analyses are presented to demonstrate that AREVA NP ATRIUM™ 10XM* fuel is hydraulically compatible with coresident ATRIUM-10 and GE14 fuel. This report also provides the hydraulic characterization of the ATRIUM 10XM, ATRIUM-10, and GE14 fuel designs for Browns Ferry. The ATRIUM 10XM fuel was analyzed with the Improved FUELGUARD™* (IFG) Lower Tie Plate (LTP), while the ATRIUM-10 fuel was analyzed with the IFG LTP and Standard FUELGUARD (SFG) LTP design.

The generic thermal-hydraulic design criteria applicable to the design have been reviewed and approved by the U.S. Nuclear Regulatory Commission (NRC) in the topical report ANF-89-98(P)(A) Revision 1 and Supplement 1 (Reference 1). In addition, thermal-hydraulic criteria applicable to the design have also been reviewed and approved by the NRC in the topical report XN-NF-80-19(P)(A) Volume 4 Revision 1 (Reference 2).

* ATRIUM and FUELGUARD are trademarks of AREVA NP.

2.0 Summary and Conclusions

ATRIUM 10XM fuel assemblies with the IFG LTP have been determined to be hydraulically compatible with the coresident fuel at Browns Ferry for the entire range of the licensed power-to-flow operating map. Detailed calculation results supporting this conclusion are provided in Section 3.2 and Table 3.2–Table 3.10. The results include the various transition cores that may be encountered for any of the Browns Ferry units.

The ATRIUM 10XM, ATRIUM-10 (SFG and IFG), and the GE14 fuel assemblies are geometrically different, but hydraulically the three designs are compatible. [

]

Core bypass flow is not adversely affected by the introduction of the ATRIUM 10XM fuel. Analyses at rated conditions show that the largest variation occurs for the GE14 to ATRIUM 10XM fuel transition with core bypass flow varying between [ ] of rated flow respectively.

Analyses demonstrate the design criteria discussed in Section 3.0 are satisfied for the Browns Ferry transition cores consisting of the following fuel combinations:

- ATRIUM 10XM, ATRIUM-10 IFG LTP and GE14
- ATRIUM 10XM and ATRIUM-10 with both SFG and IFG LTPs
- ATRIUM 10XM and ATRIUM-10 IFG LTP

These analyses were performed for the expected core power distributions and core power/flow conditions encountered during operation.

3.0 Thermal-Hydraulic Design Evaluation

Thermal-hydraulic analyses are performed to verify that design criteria are satisfied and to help establish thermal operating limits with acceptable margins of safety during normal reactor operation and AOOs. The design criteria that are applicable to the ATRIUM 10XM fuel design are described in Reference 1. To the extent possible, these analyses are performed on a generic fuel design basis. However, due to reactor and cycle operating differences, many of the analyses supporting these thermal-hydraulic operating limits are performed on a plant- and cycle-specific basis and are documented in plant- and cycle-specific reports (Reference 2).

The thermal-hydraulic design criteria are summarized below:

- **Hydraulic compatibility.** The hydraulic flow resistance of the reload fuel assemblies shall be sufficiently similar to the existing fuel in the reactor such that there is no significant impact on total core flow or the flow distribution among assemblies in the core.
- **Thermal margin performance.** Fuel assembly geometry, including spacer design and rod-to-rod local power peaking, should minimize the likelihood of boiling transition during normal reactor operation as well as during AOOs. The fuel design should fall within the bounds of the applicable empirically based boiling transition correlation approved for AREVA reload fuel. Within other applicable mechanical, nuclear, and fuel performance constraints, the fuel design should achieve good thermal margin performance.
- **Fuel centerline temperature.** Fuel design and operation shall be such that fuel centerline melting is not projected for normal operation and AOOs.
- **Rod bow.** The anticipated magnitude of fuel rod bowing under irradiation shall be accounted for in establishing thermal margin requirements.
- **Bypass flow.** The bypass flow characteristics of the reload fuel assemblies shall not differ significantly from the existing fuel in order to provide adequate flow in the bypass region.
- **Stability.** Reactors fueled with new fuel designs must be stable in the approved power and flow operating region. The stability performance of new fuel designs will be equivalent to, or better than, existing (approved) AREVA fuel designs.
- **LOCA analysis.** LOCAs are analyzed in accordance with Appendix K modeling requirements using NRC-approved models. The criteria are defined in 10 CFR 50.46.
- **Control rod drop accident analysis.** The deposited enthalpy must be less than 280 cal/gm for fuel coolability.
- **ASME overpressurization analysis.** ASME pressure vessel code requirements must be satisfied.
- **Seismic/LOCA liftoff.** Under accident conditions, the assembly must remain engaged in the fuel support.

A summary of the thermal-hydraulic design evaluation is given in Table 3.1.

3.1 *Hydraulic Characterization*

The basic geometric parameters for ATRIUM 10XM, ATRIUM-10, and GE14 fuel designs are summarized in Table 3.2. Component loss coefficients for the ATRIUM 10XM are based on tests documented and are presented in Table 3.3. These loss coefficients include modifications to the test data reduction process [

] The bare rod, ULTRAFLOW™* spacer, and UTP friction losses for ATRIUM 10XM and ATRIUM-10 are based on flow tests. The local losses for the Browns Ferry ATRIUM 10XM, ATRIUM-10 SFG, and IFG LTPs are based on pressure drop tests performed at AREVA's Portable Hydraulic Test Facility. [

] The local component (LTP, spacer, and UTP) loss coefficients for the GE14 fuel are based on flow test results.

The primary resistance for the leakage flow through the LTP flow holes is [

] The resistances for the leakage paths are shown in Table 3.3.

3.2 *Hydraulic Compatibility*

The thermal-hydraulic analyses were performed in accordance with the AREVA thermal-hydraulic methodology for BWRs (Reference 2). The methodology and constitutive relationships used by AREVA for the calculation of pressure drop in BWR fuel assemblies are presented in Reference 3 and are implemented in the XCOBRA code. The XCOBRA code predicts steady-state thermal-hydraulic performance of the fuel assemblies of BWR cores at various operating conditions and power distributions. XCOBRA received NRC approval in Reference 4. The NRC reviewed the information provided in Reference 5 regarding inclusion of water rod models in XCOBRA and accepted the inclusion in Reference 6.

Hydraulic compatibility, as it relates to the relative performance of the ATRIUM 10XM, ATRIUM-10, and GE14 fuel designs, has been evaluated. Detailed analyses were performed

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for full core GE14 fuel, full core ATRIUM-10 SFG, full core ATRIUM-10 IFG, and full core ATRIUM 10XM configurations. Analyses for mixed ATRIUM-10 SFG, ATRIUM-10 IFG, ATRIUM 10XM, and GE14 cores were performed to demonstrate that the thermal-hydraulic design criteria are satisfied for several possible Browns Ferry transition core configurations.

The hydraulic compatibility analysis is based on [

]

Table 3.4 summarizes the input conditions for the analyses. These conditions reflect two of the state points considered in the analyses: 100% power/100% flow and 62% power/37.3% flow. Table 3.4 also defines the four possible Browns Ferry core loadings for the transition core configurations. Input for other core configurations is similar in that core operating conditions remain the same and the same axial power distribution is used. Evaluations were made with the bottom-, middle-, and top-peaked axial power distributions presented in Figure 3.1. Results presented in Table 3.5–Table 3.10 and Figure 3.2–Figure 3.9 are for the bottom-peaked power distribution. Results for the middle-peaked and top-peaked axial power distributions show similar trends.

Table 3.5–Table 3.8 provide a summary of calculated thermal-hydraulic results for the transition core configurations provided in Table 3.4. Table 3.9–Table 3.10 provide a summary of results for all core configurations evaluated.

Transition Core Loading 1 (Table 3.4) is a transition core consisting of approximately one third ATRIUM 10XM fuel and one third ATRIUM-10 IFG fuel with the remainder GE14 fuel. This is a representative transition core from a full core of GE14 fuel to a full core of ATRIUM 10XM fuel, including a representative reload of ATRIUM-10 IFG fuel. The core average results and the differences between the fuel designs for both rated and off-rated statepoints are within the range considered hydraulically compatible. As shown in Table 3.5, [

] Differences in assembly flow between the fuel designs as a function of assembly power level are shown in Figure 3.2 and Figure 3.3. [ ]

[

] Core pressure drop and core bypass flow fraction are also provided for *Transition Core Loading 1* (Table 3.9–Table 3.10). Based on the reported changes in pressure drop and assembly flow caused by the transition from GE14 fuel, both the ATRIUM 10XM and ATRIUM-10 IFG designs are considered hydraulically compatible with the GE14 design since the thermal-hydraulic design criteria are satisfied.

Transition Core Loading 2 (Table 3.4) is a transition core consisting of approximately one third ATRIUM 10XM fuel and one third ATRIUM 10 IFG fuel with the remainder ATRIUM-10 SFG fuel. This is a representative transition core from a full core of ATRIUM-10 SFG fuel to a full core of ATRIUM 10XM fuel, including a representative reload of ATRIUM-10 IFG fuel. The core average results and the differences between the fuel designs for both rated and off-rated statepoints are within the range considered hydraulically compatible. As shown in Table 3.6, [

] Differences in assembly flow between the fuel designs as a function of assembly power level are shown in Figure 3.4 and Figure 3.5. [

] Core pressure drop and core bypass flow fraction are also provided for *Transition Core Loading 2* (Table 3.9–Table 3.10). Based on the reported changes in pressure drop and assembly flow caused by the transition from ATRIUM-10 SFG fuel, both the ATRIUM-10 IFG and ATRIUM 10XM designs are considered hydraulically compatible with the ATRIUM-10 SFG design since the thermal-hydraulic design criteria are satisfied.

Transition Core Loading 3 (Table 3.4) is a transition core consisting of approximately one third ATRIUM 10XM fuel with the remainder ATRIUM-10 IFG fuel. This is a representative transition core from a full core of ATRIUM-10 IFG fuel to a full core of ATRIUM 10XM fuel. The core average results and the differences between the fuel designs for both rated and off-rated statepoints are within the range considered hydraulically compatible. As shown in Table 3.7, [

] Differences in

assembly flow between the fuel designs as a function of assembly power level are shown in Figure 3.6 and Figure 3.7. [

] Core pressure drop and core bypass flow fraction are also provided for *Transition Core Loading 3* (Table 3.9–Table 3.10). Based on the reported changes in pressure drop and assembly flow caused by the transition from ATRIUM-10 IFG to ATRIUM 10XM, the ATRIUM 10XM design is considered hydraulically compatible with the ATRIUM-10 IFG design since the thermal-hydraulic design criteria are satisfied.

Transition Core Loading 4 (Table 3.4) is a transition core consisting of approximately two thirds ATRIUM 10XM fuel with the remainder ATRIUM-10 IFG fuel. This is a representative transition core for a second reload of ATRIUM 10XM at Browns Ferry. The core average results and the differences between the fuel designs for both rated and off-rated statepoints are within the range considered hydraulically compatible. As shown in Table 3.8, [

] Differences in assembly flow between the fuel designs as a function of assembly power level are shown in Figure 3.8 and Figure 3.9. [

] Core pressure drop and core bypass flow fraction are also provided for *Transition Core Loading 4* (Table 3.9–Table 3.10). Based on the reported changes in pressure drop and assembly flow caused by the second reload of ATRIUM 10XM at Browns Ferry, the ATRIUM 10XM design is considered hydraulically compatible with the co-resident fuel (ATRIUM-10 IFG) since the thermal-hydraulic design criteria are satisfied.

3.3 *Thermal Margin Performance*

Relative thermal margin analyses were performed in accordance with the thermal-hydraulic methodology for AREVA's XCOBRA code. The calculation of the fuel assembly CPR (thermal margin performance) is established by means of an empirical correlation based on results of boiling transition test programs. The CPR methodology is the approach used by AREVA to determine the margin to thermal limits for BWRs.

CPR values for ATRIUM 10XM are calculated with the ACE/ATRIUM 10XM critical power correlation (Reference 7) while the CPR values for ATRIUM-10 SFG, ATRIUM-10 IFG, and GE14 fuel are calculated with the SPCB critical power correlation (Reference 8). The NRC-approved methodology to demonstrate the acceptability of using the SPCB correlation for computing GE14 fuel CPR is presented in Reference 9. Assembly design features are incorporated in the CPR calculation through the K-factor term in the ACE correlation and the F-eff term for the SPCB correlation. The K-factors and F-effs are based on the local power peaking for the nuclear design and on additive constants determined in accordance with approved procedures. The local peaking factors are a function of assembly void and exposure.

For the compatibility evaluation, steady-state analyses evaluated ATRIUM 10XM, ATRIUM-10 SFG, ATRIUM-10 IFG, and GE14 assemblies with radial peaking factors (RPFs) between [

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Table 3.5–Table 3.8 show representative CPRs of the ATRIUM 10XM, ATRIUM-10 SFG, ATRIUM-10 IFG and GE14 fuel. Table 3.9–Table 3.10 show similar comparisons of CPR and assembly flow for the various core configurations evaluated. Analysis results indicate ATRIUM 10XM fuel will not cause thermal margin problems for the coresident fuel.

3.4 *Rod Bow*

[

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3.5 *Bypass Flow*

Total core bypass flow is defined as leakage flow through the LTP flow holes, channel seal, core support plate, and LTP-fuel support interface. Table 3.9 shows that total core bypass flow (excluding water rod flow) fraction at rated conditions changes from [ ] of rated core flow during the transition from a full GE14 fuel core to a full ATRIUM 10XM core (bottom-peaked power shape). Differences in bypass flow fractions between other transition core combinations of AREVA fuel and GE14 are either equal to or less than the full core GE14 fuel to a full core ATRIUM 10XM fuel results. [ ] In summary, adequate bypass flow will be available with the introduction of the ATRIUM 10XM fuel design and applicable design criteria are met.

3.6 *Stability*

Each new fuel design is analyzed to demonstrate that the stability performance is equivalent to or better than an existing (NRC-approved) AREVA fuel design. The stability performance is a function of the core power, core flow, core power distribution and, to a lesser extent, the fuel design. [ ] A comparative stability analysis was performed with the NRC-approved STAIF code (Reference 11). The analysis shows that the ATRIUM 10XM fuel design is equivalent to or better than other approved AREVA fuel designs.

As stated above, the stability performance of a core is strongly dependent on the core power, core flow, and power distribution in the core. Therefore, core stability is currently evaluated on a cycle-specific basis and addressed in the reload licensing report.

Table 3.1 Design Evaluation of Thermal and Hydraulic Criteria for the ATRIUM 10XM Fuel Assembly

Criteria Section	Description	Criteria	Results or Disposition
3.0	**Thermal and Hydraulic Criteria**		
3.2	Hydraulic compatibility	Hydraulic flow resistance shall be sufficiently similar to existing fuel such that there is no significant impact on total core flow or flow distribution among assemblies.	Verified on a plant-specific basis. ATRIUM 10XM demonstrated to be compatible with coresident fuel designs at Browns Ferry. [ ]
3.3	Thermal margin performance	Fuel design shall be within the limits of applicability of an approved CHF correlation.	SPCB critical power correlation is applied to both the ATRIUM-10 and GE fuel. ACE/ATRIUM 10XM critical power correlation is applied to the ATRIUM 10XM
		< 0.1% of rods in boiling transition.	Verified on cycle-specific basis for Chapter 14 analyses.
---	Fuel centerline temperature	No centerline melting.	Refer to the mechanical design report.
3.4	Rod bow	Rod bow must be accounted for in establishing thermal margins.	Design basis for fuel rod bowing is that lateral displacement of the fuel rods shall not be of sufficient magnitude to impact thermal margins.
3.5	Bypass flow	Bypass flow characteristics shall be similar among assemblies to provide adequate bypass flow.	Verified on a plant-specific basis. Analysis results demonstrate that adequate bypass flow is provided.

Table 3.1 Design Evaluation of Thermal and Hydraulic Criteria for the ATRIUM 10XM Fuel Assembly *(Continued)*

Criteria Section	Description	Criteria	Results or Disposition
3.0	**Thermal and Hydraulic Criteria** *(Continued)*		
3.6	Stability	New fuel designs are stable in the approved power and flow operating region, and stability performance will be equivalent to (or better than) existing (approved) AREVA fuel designs.	Core stability behavior is evaluated on a cycle-specific basis. ATRIUM 10XM channel and core decay ratios have been demonstrated to be equivalent to or better than other approved AREVA fuel designs.
---	LOCA analysis	LOCA analyzed in accordance with Appendix K modeling requirements. Criteria defined in 10 CFR 50.46.	Approved Appendix K LOCA model. Plant- and fuel-specific analysis with cycle-specific verifications.
---	CRDA analysis	< 280 cal/gm for coolability.	Cycle-specific analysis is performed.
---	ASME over-pressurization analysis	ASME pressure vessel core requirements shall be satisfied.	Cycle-specific analysis is performed.
---	Seismic/LOCA liftoff	Assembly remains engaged in fuel support.	Refer to the mechanical design report.

**Table 3.2 Comparative Description of
Browns Ferry ATRIUM 10XM and Coresident Fuel**

Fuel Parameter	ATRIUM 10XM	ATRIUM-10	GE14
Number of fuel rods			
Full-length fuel rods	79	83	78
PLFRs	12	8	14
Fuel clad OD, in	0.4047	0.3957	0.404
Number of spacers	9	8	8
Active fuel length, ft			
Full-length fuel rods	12.500	12.454	12.500
PLFRs	6.25	7.5	7.0
Hydraulic resistance characteristics	Table 3.3	Table 3.3	Table 3.3
Number of water rods	1	1	2
Water rod OD, in	1.378*	1.378*	0.980

* Square water channel outer width.

Table 3.3 Hydraulic Characterization Comparison Between Browns Ferry Unit ATRIUM 10XM and Coresident Fuel Assemblies

Table 3.3 Hydraulic Characterization Comparison Between Browns Ferry Unit ATRIUM 10XM and Coresident Fuel Assemblies
(continued)

**Table 3.4 Browns Ferry
Thermal-Hydraulic Design Conditions**

Reactor Conditions	100%P / 100%F	62%P / 37.3%F
Core power level, MWt	3458	2146
Core exit pressure, psia	1060	987
Core inlet enthalpy, Btu/lbm	524.7	492.2
Total core coolant flow, Mlbm/hr	102.5	38.2
Axial power shape	Bottom-peaked (Figure 3.1)	Bottom-peaked (Figure 3.1)

	Number of Assemblies	
	Central Region	Peripheral Region
Transition Core Loading 1		
[ ]		
Transition Core Loading 2		
[ ]		
Transition Core Loading 3		
[ ]		
Transition Core Loading 4		
[ ]		

**Table 3.5 Browns Ferry Transition Core Loading 1
Thermal-Hydraulic Results**

**Table 3.6 Browns Ferry Transition Core Loading 2
Thermal-Hydraulic Results**

Table 3.7 Browns Ferry Transition Core Loading 3 Thermal-Hydraulic Results

**Table 3.8 Browns Ferry Transition Core Loading 4
Thermal-Hydraulic Results**

Table 3.9 Browns Ferry Thermal-Hydraulic Results at 100% CLTP and 100% Core Flow Conditions

Table 3.10 Browns Ferry Thermal-Hydraulic Results at 62% CLTP and 37.3% Core Flow Conditions

[ ]

Figure 3.1 Axial Power Shapes

Figure 3.2 Transition Core Loading 1:
Hydraulic Demand Curves 100% CLTP / 100% Flow

[ ]

**Figure 3.3 Transition Core Loading 1:
Hydraulic Demand Curves 62% CLTP / 37.3% Flow**

**Figure 3.4 Transition Core Loading 2:
Hydraulic Demand Curves 100% CLTP / 100% Flow**

Figure 3.5 Transition Core Loading 2:
Hydraulic Demand Curves 62% CLTP / 37.3% Flow

**Figure 3.6 Transition Core Loading 3:
Hydraulic Demand Curves 100% CLTP / 100% Flow**

**Figure 3.7 Transition Core Loading 3:
Hydraulic Demand Curves 62% CLTP / 37.3% Flow**

[ ]

Figure 3.8 Transition Core Loading 4:
Hydraulic Demand Curves 100% CLTP / 100% Flow

Figure 3.9 Transition Core Loading 4:
Hydraulic Demand Curves 62% CLTP / 37.3% Flow

4.0 References

1. ANF-89-98(P)(A) Revision 1 and Supplement 1, *Generic Mechanical Design Criteria for BWR Fuel Designs*, Advanced Nuclear Fuels Corporation, May 1995.

2. XN-NF-80-19(P)(A) Volume 4 Revision 1, *Exxon Nuclear Methodology for Boiling Water Reactors: Application of the ENC Methodology to BWR Reloads*, Exxon Nuclear Company, June 1986.

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

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

5. Letter, R. A. Copeland (ANF) to R. C. Jones (USNRC), "Explicit Modeling of BWR Water Rod in XCOBRA," RAC:002:90, January 9, 1990.

6. Letter, R. C. Jones (USNRC) to R. A. Copeland (ANF), no subject (regarding XCOBRA water rod model), February 1, 1990.

7. ANP-10298PA Revision 0, *ACE/ATRIUM 10XM Critical Power Correlation*, AREVA NP, March 2010.

8. EMF-2209(P)(A) Revision 3, *SPCB Critical Power Correlation*, AREVA, September 2009.

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

10. ANP-10298PA Revision 0 Supplement 1P Revision 0, *Improved K-factor Model for ACE/ATRIUM 10XM Critical Power Correlation*, AREVA NP, December 2011.

11. EMF-CC-074(P)(A) Volume 1, *STAIF – A Computer Program for BWR Stability Analysis in the Frequency Domain;* and Volume 2, *STAIF – A Computer Program for BWR Stability Analysis in the Frequency Domain – Code Qualification Report*, Siemens Power Corporation, July 1994.

12. ANP-3140(P) Revision 0, *Browns Ferry Units 1, 2, and 3 Improved K-factor Model for ACE/ATRIUM 10XM Critical Power Correlation,* AREVA NP, August 2012.