ATTACHMENT 31

ANP-3327NP, Evaluation of AREVA Fuel Thermal-Hydraulic Performance for Browns Ferry at EPU (Non-Proprietary)

ANP-3327NP
Revision 1

Evaluation of AREVA Fuel Thermal-Hydraulic Performance for Browns Ferry at EPU

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AREVA Inc.

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Nature of Changes

Item	Page	Description and Justification
1.	3-5	Section 3.3 discussion regarding the reference to the ACE/ATRIUM 10XM Critical Power Correlation is modified to the current Browns Ferry Technical Specification approvals.
2.	4-1	Added Reference 11 and modified Reference 7 consistent with the description in Item 1.

Contents

Tables

Figures

Nomenclature

Acronym	Definition
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
EPU	Extended Power Uprated
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
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 Inc. ATRIUM™ 10XM* fuel is hydraulically compatible with ATRIUM-10 fuel at EPU conditions. This report also provides the hydraulic characterization of the ATRIUM 10XM and ATRIUM-10 fuel designs for Browns Ferry.

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 is a trademark of AREVA Inc.

2.0 Summary and Conclusions

The thermal-hydraulic evaluations presented in this report are for the various, expected core configurations that includes ATRIUM 10XM and ATRIUM-10 fuel designs at EPU operation. These fuel designs have been determined to be hydraulically compatible at Browns Ferry for the entire range of the licensed EPU power-to-flow operating map. Detailed calculation results supporting this conclusion are provided in Section 3.2 and Tables 3.2 to 3.8.

The ATRIUM 10XM and the ATRIUM-10 fuel assemblies are geometrically different, but hydraulically the two designs are compatible at EPU operation. [

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Core bypass flow is not significantly affected by any combination core loading of ATRIUM 10XM and ATRIUM-10 fuel for EPU operation. Analyses at rated conditions show the core bypass flow varying between [ ] of rated flow.

Analyses demonstrate the design criteria discussed in Section 3.0 are satisfied for the Browns Ferry EPU cores configuration consisting of ATRIUM 10XM and ATRIUM-10 fuel combinations. These analyses were performed for expected EPU core power distributions and core 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 AREVA fuel designs 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 < 280 cal/gm for fuel coolability. AREVA will target to limit maximum deposited enthalpies to < 230 cal/gm.
- **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 and ATRIUM-10 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 and ATRIUM-10 LTPs are based on pressure drop tests performed at AREVA's Portable Hydraulic Test Facility. [

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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.

* ULTRAFLOW is a trademark of AREVA Inc.

Hydraulic compatibility, as it relates to the relative performance of the ATRIUM 10XM and ATRIUM-10 fuel designs, has been evaluated. This report provides ATRIUM-10 and ATRIUM 10XM mixed core analysis for possible EPU conditions. These analyses were performed to demonstrate that the thermal-hydraulic design criteria are satisfied for expected Browns Ferry core configurations under EPU operation.

The hydraulic compatibility analysis is based on [

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Table 3.4 summarizes the input conditions for the analyses. These conditions reflect two of the statepoints considered in the analyses: 100% EPU power/100% flow and 54.3% EPU power/37.3% flow. Table 3.4 also defines the two Browns Ferry core configurations presented in this report. 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 Tables 3.5 to 3.8 and Figures 3.2 and 3.5 are for bottom peaked power distribution. Results for the middle-peaked and top-peaked axial power distributions show similar trends.

Table 3.5–Table 3.6 provide a summary of calculated thermal-hydraulic results for the core configurations provided in Table 3.4. Tables 3.7 to 3.8 provide a summary of results for all core configurations evaluated.

Core Loading 1 (Table 3.4) is a core consisting of approximately one third ATRIUM 10XM fuel with the remainder ATRIUM-10 fuel. This represents a core with a single reload 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 3.5, [

] 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 *Core Loading 1* (Table 3.7–3.8). Based on the reported changes in pressure drop and assembly flow caused by the first reload of ATRIUM-10XM, the ATRIUM 10XM design is considered hydraulically compatible with the ATRIUM-10 design for EPU operation since the thermal-hydraulic design criteria are satisfied.

Core Loading 2 (Table 3.4) is a core consisting of approximately two thirds ATRIUM 10XM fuel with the remainder ATRIUM-10 fuel. This represents a core with two reloads 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 3.6, [

]

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 *Core Loading 2* (Table 3.7–3.8). 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 ATRIUM-10 fuel design for EPU operation 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 fuel are calculated with the ACE/ATRIUM 10XM critical power correlation (References 7 and 11) while the CPR values for ATRIUM-10 fuel are calculated with the SPCB critical power correlation (Reference 8). 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 and ATRIUM-10 fuel assemblies with radial peaking factors (RPFs) between [ ] and representative K-factors and F-effs. Tables 3.5 to 3.6 show representative CPRs of the ATRIUM 10XM and ATRIUM-10. Table 3.7–3.8 show similar comparisons of CPR and assembly flow for the various core the mixed configurations evaluated. Analysis results indicate ATRIUM 10XM fuel will not adversely affect the thermal margin performance of the ATRIUM 10 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 3.7 shows that total core bypass flow (excluding water rod flow) fraction at rated conditions changes from [ ] of rated core flow during the core configurations 1 and 2 (bottom-peaked power shape). [

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[ ] In summary, adequate bypass flow will be available for a core mixture of ATRIUM 10XM and ATRIUM 10 fuel design under EPU operation 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 10). 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 ATRIUM 10 fuel designs at Browns Ferry at EPU conditions. [ ]
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 the ATRIUM-10 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. AREVA will target to limit maximum deposited enthalpies to < 230 cal/gm.
---	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 ATRIUM-10 Fuel

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

* Square water channel outer width.

Table 3.3 Hydraulic Characterization Comparison Between Browns Ferry ATRIUM 10XM and ATRIUM-10

Table 3.4 Browns Ferry EPU
Thermal-Hydraulic Design Conditions

Reactor Conditions	100%P / 100%F	54.3%P / 37.3%F
Core power level, MWt	3952	2146
Core exit pressure, psia	1060	987
Core inlet enthalpy, Btu/lbm	523.2	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
Core Loading 1		
[		]
Core Loading 2		
[		]

Table 3.5 Browns Ferry EPU Core Loading 1
Thermal-Hydraulic Results

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

Table 3.7 Browns Ferry Thermal-Hydraulic Results at 100% EPU and 100% Core Flow Conditions

[ ]

Table 3.8 Browns Ferry Thermal-Hydraulic Results at 54.3% EPU and 37.3% Core Flow Conditions

[ ]

[ ]

Figure 3.1 Axial Power Shapes

**Figure 3.2 Core Loading 1:
Hydraulic Demand Curves 100% EPU / 100% Flow**

Figure 3.3 Core Loading 1:
Hydraulic Demand Curves 54.3% EPU / 37.3% Flow

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

Figure 3.5 Core Loading 2:
Hydraulic Demand Curves 54.3% EPU / 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 Inc., 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. 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.

11. 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, Inc., August 2012.