ENCLOSURE 2

FLN-2007-029

NEDO-32851-A, Revision 4,

GEXL14 Correlation for GE14 Fuel

Non-Proprietary Information

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Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

NEDO-32851-A
Revision 4
Class I
eDRF 0000-0066-2872
September 2007

NON-PROPRIETARY INFORMATION

GEXL14 Correlation for GE14 Fuel

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

August 3, 2007

Andrew A. Lingenfelter, Manager
GNF Engineering
Global Nuclear Fuel- Americas, LLC
P.O. Box 780, M/C F12
Wilmington, NC 28402

SUBJECT: FINAL SAFETY EVALUATION FOR GLOBAL NUCLEAR FUEL (GNF) TOPICAL REPORT (TR) NEDC-32851P, REVISION 2 ,"GEXL14 CORRELATION FOR GE14 FUEL" (TAC NO. MD5486)

Dear Mr. Lingenfelter:

By letter dated September 25, 2001, GNF submitted TR NEDC-32851P, Revision 2, "GEXL14 Correlation for GE14 Fuel," to the U.S. Nuclear Regulatory Commission (NRC) staff. The NRC staff closed the review in a letter dated July 11, 2003, while GNF conducted additional testing. By letter dated April 13, 2007, GNF submitted Supplement 1 to TR NEDC-32851P, Revision 2, "GEXL14 Correlation for GE14 Fuel," which provided the additional data. By letter dated May 30, 2007, an NRC draft safety evaluation (SE) regarding our approval of TR NEDC-32851P, Revision 2, was provided for your review and comments. By letter dated June 25, 2007, GNF commented on the draft SE. The NRC staff's disposition of GNF comments on the draft SE are discussed in Attachment 2 to the final SE enclosed with this letter.

The NRC staff has found that TR NEDC-32851P, Revision 2, is acceptable for referencing in licensing applications for General Electric fueled boiling water reactors to the extent specified and under the limitations delineated in the TR and in the enclosed final SE. The final SE defines the basis for our acceptance of the TR.

Our acceptance applies only to material provided in the subject TR. We do not intend to repeat our review of the acceptable material described in the TR. When the TR appears as a reference in license applications, our review will ensure that the material presented applies to the specific plant involved. License amendment requests that deviate from this TR will be subject to a plant-specific review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that GNF publish accepted proprietary and non-proprietary versions of this TR within three months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed final SE after the title page. Also, they must contain historical review information, including NRC requests for additional information and your responses. The accepted versions shall include an "-A" (designating accepted) following the TR identification symbol.

If future changes to the NRC's regulatory requirements affect the acceptability of this TR, GNF and/or licensees referencing it will be expected to revise the TR appropriately, or justify its continued applicability for subsequent referencing.

Sincerely,

Ho K. Nieh, Deputy Director
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 712

Enclosures: 1. Non-proprietary Final SE
2. Proprietary Final SE

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August 3, 2007

If future changes to the NRC's regulatory requirements affect the acceptability of this TR, GNF and/or licensees referencing it will be expected to revise the TR appropriately, or justify its continued applicability for subsequent referencing.

Sincerely,

/RA/

Ho K. Nieh, Deputy Director
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

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Enclosures: 1. Non-proprietary Final SE
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*No major changes to SE input. NRR-043

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FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT NEDC-32851P, REVISION 2

"GEXL14 CORRELATION FOR GE14 FUEL"

GLOBAL NUCLEAR FUEL

PROJECT NO. 712

1.0 INTRODUCTION AND BACKGROUND

By letter dated September 25, 2001 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML012760506), Reference 1, Global Nuclear Fuel - Americas, LLC, hereafter referred to as GNF, submitted a request to the U. S. Nuclear Regulatory Commission (NRC) to review topical report (TR) NEDC-32851P, Revision 2, "GEXL14 Correlation for GE14 Fuel." This revision includes changes to the correlation statistics for the GNF 10x10 fuel design based entirely on experimental data and additional testing of the GE14 fuel. The review of TR NEDC-32851P, Revision 2, was closed by the NRC staff in letter dated July 11, 2003, while GNF conducted additional testing to obtain critical power data for GE14 top peaked axial power shape. Supplement 1 to TR NEDC-32851P, Revision 2, was provided by letter dated April 13, 2007 (ADAMS Accession No. ML071080327) and proprietary enclosure (ADAMS Accession No. ML071080333), Reference 2, which includes the additional test data.

The TR presents the GEXL14 correlation development for determination of the minimum critical power ratio (MCPR) during normal operation and postulated transient events for the General Electric Corporation (GE) boiling water reactor (BWR). The GEXL14 correlation is a critical quality and boiling length correlation used to predict the occurrence of boiling transition in BWR fuel designs. The test data used to support the development of the correlation include full-scale simulations of 7x7, 8x8, 9x9, and 10x10 fuel assemblies that were obtained at the GE ATLAS test facility in San Jose, California. The database supporting the basic GEXL correlation includes over 20,000 full-scale boiling transition data points and encompasses all of the fuel assembly designs and operating regions for BWRs. Testing has been performed in the ATLAS facility to demonstrate that the GEXL correlation can be used to predict the onset of boiling transition during postulated transient conditions that are analyzed in the safety analysis process.

The specific GEXL14 correlation developed for use in the core design and safety analysis process is intended to accurately predict the expected critical power performance of the fuel assembly design. In the core design process, the GEXL14 correlation is used to determine the expected thermal margin for the operating cycle. In the safety analysis process, the GEXL14 correlation is used in the determination of the change in critical power transients and in the determination of an acceptable MCPR safety limit. Based on the supporting test database, the TR concludes that the safety related conditions have been satisfied with respect to the development of an acceptable critical power correlation.

Revision 1 of TR NEDC-32851P, which describes the GEXL14 critical power correlation for GE14 fuel, was transmitted to the NRC by letter dated August 8, 2000. The lead plant application for GE14 fuel was the Duane Arnold Energy Center (DAEC) Extended Power Uprate (EPU). The DAEC Technical Specification Change Request for EPU, Reference 4, referred to TR NEDC-32851P, Revision 1, for critical power determination for the new fuel. As part of the DAEC EPU review, the NRC staff evaluated Revision 1 of the TR, including the experimental database used for the development of the GEXL14 critical power ratio (CPR) correlation for the GE14 (10x10) fuel lattice design. Several issues were identified by the NRC staff. The summary of the NRC staff's findings and GNF's corrective actions to resolve the issues are discussed below.

During the week of March 26, 2001, four members of the NRC staff visited the GNF engineering and manufacturing facility in Wilmington, North Carolina. The purpose of the visit was to perform an onsite review of the safety analyses and system and component performance evaluations used to support the proposed EPU. The areas covered by the review included:

1. Fuel performance of the 10x10 GE14 fuel lattice design used for DAEC, including available post-irradiation examination data;

2. Review of the GEXL14 correlation database for GE14 fuel;

3. Verification that the experimental database range covered DAEC's expected operating ranges or state points (i.e., pressures, mass fluxes, inlet subcooling) for all three axial profiles (cosine, inlet-peaked, and outlet-peaked); and

4. Review of the GE14 fuel design compliance with the NRC-approved methodology.

During the audit, the NRC staff evaluated the thermal-hydraulic compatibility of the DAEC resident fuel types in the low-flow/high power conditions with off-normal void distribution.

A formal Request for Additional Information letter summarizing the audit issues was issued in June 2001. Attachment 1 provides a summary of the chronology of events related to the TR review. Attachment 2 provides the resolution by NRC to the comments submitted by GNF on June 25, 2007.

2.0 REGULATORY EVALUATION

The regulation at Title 10 of the *Code of Federal Regulations* (10 CFR), Section 50.34, "Contents of applications; technical information," requires that Safety Analysis Reports be submitted that analyze the design and performance of structures, systems, and components provided for the prevention of accidents and the mitigation of the consequences of accidents. As part of the core reload design process, licensees (or vendors) perform reload safety evaluations to ensure that their safety analyses remain bounding for the design cycle. To confirm that the analyses remain bounding, licensees confirm that key inputs to the safety analyses, such as the CPR are conservative with respect to the current design cycle. If key safety analysis parameters are not bounded, a re-analysis or re-evaluation of the affected transients or accidents is performed to ensure that the applicable acceptance criteria are satisfied.

The NRC staff review was based on the evaluation of the technical merit and compliance with any applicable regulations associated with reviews of TRs.

General Design Criterion (GDC)-10, "Reactor design," of Appendix A to 10 CFR Part 50 is intended to ensure that reactor cores are designed with appropriate margin such that specified acceptable fuel design limits are not exceeded during normal operation or anticipated operational occurrences (AOOs).

To ensure compliance with GDC-10, the NRC staff confirms that the thermal and hydraulic design of the core and the reactor coolant system have been accomplished using acceptable analytical methods, is equivalent to or is a justified extrapolation from proven designs, provides acceptable margins of safety from conditions which would lead to fuel damage during normal reactor operation and AOOs, and is not susceptible to thermal-hydraulic instability.

Reference 5, NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," Section 4.4, "Thermal and Hydraulic Design," describes the normal review of thermal and hydraulic design and requires that additional independent audit analyses be performed for new CPR correlations.

3.0 TECHNICAL EVALUATION

The GE critical quality - boiling length critical power correlation (GEXL) was developed to accurately predict the onset of boiling transition in BWR fuel assemblies during both steady-state and reactor transient conditions. The use of the GEXL correlation is necessary for determining the MCPR operating limits resulting from transient analysis, the MCPR safety limit analysis, and the core operating performance and design. The GEXL correlation is an integral part of the transient analysis methodology used by GNF. It is used to confirm the adequacy of the MCPR operating limit, and it can be used to determine the time of onset of boiling transition in the analysis of other events.

The GEXL correlation has been used in the safety analysis process for GE fueled BWRs since 1974. The GEXL correlation is based on the relationship of critical quality with boiling length. It expresses bundle average critical quality as a function of boiling length, thermal diameter, system pressure, lattice geometry, local rod peaking pattern (R-factor), mass flux, and annular flow length.

During the DAEC EPU audit, the NRC staff reviewed GE's experimental database used to develop the GEXL14 CPR correlation for the GE14 (10x10) fuel lattice design. The EPU onsite audit findings and the resolutions to identified open items are discussed below:

(1) The NRC staff found that in its CPR correlation methodology, GNF was using the COBRAG computer code (with the GEXL correlation built in) to generate data instead of using experimental data obtained from their critical heat flux test facility in San Jose, California. The use of artificial data instead of raw data affects the validity of the statistical results obtained from this methodology. The statistical results are important because they are used in the calculation of the safety limit MCPR (SLMCPR) for all BWRs that use GE14 fuel. The correlation uncertainty associated with the data points affects the uncertainty of the safety limit calculations, as well as the degree of conservatism that is used to establish the reactor operating limits.

The NRC staff is aware of the difficulty in predicting critical power phenomena in the upper portion of the core because of the active multiple phase transitions and the part-length rods present in GE14 fuels. The COBRAG code has never been reviewed by the NRC staff for this purpose. Consequently, GNF agreed to remove the COBRAG-generated data from the development of the GEXL correlation for the GE14 fuel design.

(2) The NRC staff was concerned that GNF had not conducted sufficient testing of the new GE14 fuel to adequately evaluate the GEXL14 correlation. The NRC staff discovered that the experimental data collected to develop and validate the GEXL14 correlation did not include inlet and outlet power shapes. GNF pointed out to the NRC staff that there are similarities between the GE11 (9x9) fuel lattice design and the GE14 (10x10) fuel lattice designs, namely the presence of part-length rods. However, the NRC staff believes that there are also significant differences, such as the locations of the part-length rods relative to the water holes in the GE14 fuel design. To resolve the issue, GNF proposed to obtain additional critical heat flux (CHF) data to validate the GEXL14 correlation. In the interim, GNF proposed a self imposed "additional correlation uncertainty" while they obtained the additional data.

3.1 Supplemental Data and Power Shape Sensitivity Comparison

Subsequent to the NRC staff's finding during the DAEC EPU audit, GNF obtained (inlet/bottom peaked) data from its ATLAS facility. GNF also obtained (outlet/top peaked) data from Stern Laboratory in Ontario, Canada. This additional data was used to validate the GE14 correlation uncertainty and CHF behavior for inlet and outlet peaked power profiles.

The ATLAS facility critical power data used to develop the GEXL14 correlation contained bottom peaked and cosine axial power shape data, but no top peaked axial power shape data. Additional critical power data have subsequently been collected from the Stern Laboratory test facility. A total of [ ] critical power data points were collected to verify the axial power shape sensitivity. These data points were not used in the development of the GEXL14 correlation, but were used to validate the capability of the GEXL14 correlation to predict the trend with axial power shape. The GEXL14 correlation coefficients were not adjusted in this process, only the additive constants were determined for the rod-to-rod peakings used in the Stern Laboratory tests.

The statistics for the validation of the GEXL14 correlation against the Stern Laboratory data is given in the Table 4-10 of TR NEDC-32851P, Supplement 1. Analysis of the ATLAS facility and Stern Laboratory data show that the numbers compare very well to the GEXL14 correlation statistics for the ATLAS facility data used to develop the correlation, as shown in Table 1 below. The correlation statistics for the ATLAS facility data had a mean ratio of calculated to measured critical power (ECPR) of [ ] and a standard deviation of [ ] percent. The General Electric Thermal Analysis Basis method was used to account for the absence of inlet/outlet peaked experimental data resulting in an increase in the licensing basis uncertainty to [ ] percent. It is seen from the close agreement between these data that the GEXL14 correlation predicts the trend with axial power shape very well.

The interim additional correlation uncertainty was calculated using a conservative estimate of the outlet peaked standard deviation. A correlation uncertainty of [ ] percent has been used for outlet peaked power shapes in all GEXL14 applications. This has resulted in as much as a [ ] percent increase in the SLMCPR for operating plants with GE14 fuel. When additional data was obtained and the correlation statistics were determined, the correlation upskew and downskew CPR uncertainties were found to be within the original correlation total uncertainty. Therefore, the original correlation uncertainty of [ ] percent can be reinstated.

Using the actual calculated standard deviation and considering the data in Table 1, the overall uncertainty is calculated to be [ ] percent. This is within the original licensing basis uncertainty of [ ] percent.

Table 1. GEXL14 Statistics versus Experimental Data

	Bottom Peaked Axial Power Shape (Stern)	Top Peaked Axial Power Shape (Stern)	Cosine Power Shape (ATLAS)
Number of Data Points	[ ]	[ ]	[ ]
Mean ECPR, μ	[ ]	[ ]	[ ]
Standard Deviation	[ ]	[ ]	[ ]

Table 1 demonstrates that these uncertainties are within the original licensing basis correlation uncertainty of [ ] percent for various axial power shapes.

Figure 4-1 of TR NEDC-32851P, Supplement 1, compares the power shape sensitivity between inlet/outlet peak power shapes and cosine for GE14 (GEXL14), GE12 (GEXL10), GE11 (GEXL07), and GE13 (GEXL09). The latter two are correlations for 9x9 bundles for which ATLAS facility tests for all three power shapes were performed. The comparison shows that the outlet peak relative performance for GEXL14 is very consistent with the outlet peak relative performance for previous 9X9 fuel. This shows that additional spacers at varying locations within the bundle do not introduce any new sensitivities into the axial power shape effects. The agreement of the GEXL14 correlation predictions with the Stern Laboratory data for inlet and outlet peaked axial power shapes confirms this observation and demonstrates that the GEXL correlation accurately predicts the sensitivity with axial power shape.

3.2 High R-factor

The data collected in the ATLAS facility and the standard critical power database from the Stern Laboratory tests had R-factors up to [ ]. This R-factor range had previously been judged to be sufficient to cover fully controlled bundles. [

], MFN-05-095, J. S. Post to NRC, "Part 21 Notification Completion, Critical Power Determination for GE14 and GE12 with Zircaloy Spacers", September 20, 2005 (Reference 6), and FLN-2005-034, A. A. Lingenfelter to NRC, "Recent Experimental Thermal Hydraulics and GNF2 Licensing Meeting, October 26-27, 2005", December 15, 2005 (Reference 7), [

] However, GNF conducted an additional test at the Stern Laboratory simulating a fully controlled bundle and having a very high R-factor of 1.26. Comparison of the ECPR results from the Stern Laboratory test with those of the GEXL14 correlation prediction of an ECPR of [ ] and a standard deviation of [ ] demonstrates that the extension of the upper R-factor application range to 1.25 is justified.

The pressure range was also adjusted. The previous ATLAS facility testing covered the pressure range from 800 to 1300 psia. The Stern Laboratory testing extended this range from 700 to 1400 psia.

The GEXL14 correlation for GE14 fuel is valid over the range stated in Table 2 below.

Table 2. GEXL14 Applicability Range

Pressure	4.8 to 9.7 MPa (700 to 1400 psia)
Mass Flux	*136 to 2448 kg/sec-m^2 (0.1 x 10^6 to 1.8 x 10^6 lb/hr-ft^2)
Inlet Subcooling	0 to 233 kJ/kg (0 to 100 Btu/lb)
R-factor	*0.9 - 1.25

*exception in R-factor and Mass flux plane, the parameters should also satisfy:

$(1.2\text{-}R)/0.05 \geq (G\text{-}1.5)/0.3$ for $1.15 < R < 1.20$

$(1.25\text{-}R)/0.05 \geq (G\text{-}1.3)/0.2$ for $1.20 < R < 1.25$

The upper mass flux range for $R < 1.15$ is 2448 kg/sec-m^2

4.0 CONCLUSION

The GEXL14 correlation has been validated against ATLAS facility data for cosine and inlet peaked axial power shapes and against Stern Laboratory data for inlet and outlet peaked axial power shapes. These comparisons show that the axial power shape sensitivity is well predicted by the GEXL correlation. The power shape sensitivity has been shown to be very similar for the different 9X9 and 10x10 fuel product lines.

The TR NEDC-32851P was reviewed as part of the DAEC EPU submittal. The technical issues which were discovered during the DAEC EPU review were resolved in the EPU audit and supplemental documentation (Reference 8). On the basis of these prior reviews and the NRC staff review of Supplement 1 to TR NEDC-32851P, Revision 2, the NRC staff considers the methodology described in TR NEDC-32851P, Revision 2, acceptable. GNF satisfactorily responded to the issues with timely and appropriate corrective actions, explanations, and additional test data. Therefore, on the basis of the above review and justification, the NRC staff concludes that the proposed GEXL14 critical power correlation is acceptable.

5.0 REFERENCES

1. G. A. Watford to NRC, "GEXL14 Correlation for GE14 Fuel, NEDC-32851P Revision 2 and GEXL10 Correlation for GE12 Fuel with Inconel Spacers, NEDC-32464P Revision 2," September 25, 2001 (ADAMS Accession No. ML012760506).

2. A. A. Lingenfelter to NRC, "Supplement 1 to GEXL14 Correlation for GE14 Fuel, NEDC-32851P, Revision 2, September 2001," April 13, 2007 (ADAMS Accession No. ML071080327) and proprietary enclosure (ADAMS Accession No. ML071080333).

3. NEDE-24011-P-A-14, General Electric Standard Application for Reactor Fuel (GESTAR II), June 2000 (ADAMS Accession No. ML011230173).

4. Nuclear Management Company to the NRC, "Duane Arnold Energy Center, Docket No. 331, Op. License No. DPR-49, Technical Specification Change Request (TSCR-042): 'Extended Power Uprate,'" November 16, 2000, and attachments (ADAMS Accession No. ML003771301).

5. NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," April 1996.

6. J. S. Post to NRC, "Part 21 Notification Completion, Critical Power Determination for GE14 and GE12 Fuel with Zircaloy Spacers," September 20, 2005 (ADAMS Accession No. ML052690084).

7. A. A. Lingenfelter to NRC, "Recent Experimental Thermal Hydraulics and GNF2 Licensing Meeting, October 26-27, 2005," December 15, 2005 (ADAMS Accession No. ML060050548).

8. Duane Arnold Energy Center, NRC Staff Safety Evaluation for Amendment No. 243, Extended Power Uprate, November 6, 2001 (ADAMS Accession No. ML013050342).

Attachments: 1. Chronology of Events
2. Summary of Comments and Resolution

Principle Contributors: J. Gilmer
A. Attard

Date: August 3, 2007

CHRONOLOGY OF EVENTS FOR APPROVAL OF GEXL14

CORRELATION TOPICAL REPORT (TR) NEDC-32851P

Date	Description
September 1999	Revision 1 of TR NEDC-32851P issued.
March 26, 2001	Duane Arnold Energy Center (DAEC) extended power uprate (EPU) audit conducted at Global Nuclear Fuel (GNF) (identified requests for additional information (RAIs) related to review of TR NEDC 32851P, Revision 1).
March 27, 2001	GNF letter and attached responses to RAIs regarding GE14 review.
June 2001	Presentation to the U.S. Nuclear Regulatory Commission (NRC) staff on axial power shape sensitivity (echoed GNF's position provided in responses to Revision 1 in March 2001).
September 2001	GNF submitted TR NEDC-32851P, Revision 2, to the NRC staff for review.
November 2001	Safety Evaluation for DAEC EPU accepted by NRC.
February 2002	NRC staff meeting with GNF to discuss TR NEDC-32851P, Revision 2: corrective actions, commitment to proposed testing program, preventative actions, and double hump considerations.
April 2002	GNF letter describing proposed interim evaluation process.
May 2003	GNF letter committing to additional testing. Letter referenced the February 2002 testing commitment and suggested that there was no need for NRC review because GNF would be compliant with GESTAR II when the additional data was acquired.
July 2003	NRC letter rejecting GNF position that correlation issues are addressed by GESTAR, Amendment 22, requiring no staff review when the additional data is acquired.
January/February 2005	GNF conducts additional tests at Stern Laboratory to obtain additional data for the GEXL14 correlation.
March 2005	Final SE on GESTAR II, Amendment 27.
October 2005	GNF presentation to the NRC staff on testing results to resolve test data deficiency for the GE14 fuel.
April 2007	GNF letter provided Supplement 1 to NEDC-32851P, Revision 2.

SUMMARY OF COMMENTS AND RESOLUTION

Location	Comment	Resolution
Table 2	The units on the mass flux are shown as 106 lb/hr-ft2 but should be 10^6 lb/hr-ft2 . This may be a Wordperfect-MS Word conversion problem.	Accepted.
Chronology of Events Table September 1999	Based on our records TR NEDC-32851, Revision 1, was not submitted for review. The date on Revision 1 is September 1999.	Accepted.
Chronology of Events Table February 2002	The commitment to perform additional testing was made at this meeting (FLN_2002_004 dated February 12, 2002).	Accepted.
Chronology of Events Table May 2003	This letter referenced the February 2002 commitment and suggested that there was no need for an NRC review because GNF would be compliant with GESTAR II when the additional data was acquired.	Accepted.
Chronology of Events Table July 2003	NRC letter rejecting GNF position that correlation issues are addressed by GESTAR II, Amendment 22, without review when the additional data was complete.	Accepted.
Chronology of Events Table March 2005	The GESTAR II, Amendment 27, does not include information or relationships to the GEXL14 correlation.	Accepted.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

Revision Status

Revision Number	Section	Description of Change
2	3	More detail added describing GEXL-Plus
	3, 4, 7	Addition of new ATLAS data for GEXL14 evaluation
	4	All COBRAG material moved to Appendix A and GETAB methods for calculation of GEXL14 uncertainties added
	6	Correction of Figure 6-2 Axis Labels
	8	R-factor Calculation Method promoted from Appendix A in Rev. 1 to Section 8 in Rev. 2
	8	Addition of applicability statement for R-factor Calculation Methods to GE14 fuel per NRC requirement
	8	Correction to Relative Void Fraction line in Figure 8-1 GE14 Axial Shapes for Rod Power Integration
	10	References added
	All	Revision bars added to right margin signifying additions/changes to the text compared to Rev. 1
3	Revision 3 is a version that was used in Europe	
4	**Revision 4 is the Acceptance version of Revision 2 including Supplement 1 as reviewed and approved**	
	Generic	Added new Affidavit and updated all Proprietary markings per the current marking convention
	Abstract	Added editorial prose in the 1st paragraph reflecting the additional Stern Laboratories Inc. data
	Section 3	Added to end of Section 3 covering Stern Laboratories Inc. test sections and power shapes
	Section 4	Added test matrix information to Section 4.2
		Replaced Section 4.7 and 4.8
	Section 5	Updated GEXL application range in Section 5.2
		Table 5-1 in Section 5.4.5 is replaced
		Section 5.4.6 is replaced

Abstract

The GE correlation for determining the minimum critical power ratio (MCPR) during normal operation and postulated transient events for the boiling water reactor (BWR) and its development is presented. The basic GEXL correlation is a critical quality and boiling length correlation used to predict the occurrence of boiling transition in BWR fuel designs. The test data used to support the development of the correlation include full-scale simulations of 7x7, 8x8, 9x9, and 10x10 fuel assemblies that were obtained at the GE ATLAS test facility in San Jose, California. The database supporting the basic GEXL correlation includes over 20,000 full-scale boiling transition data points and encompasses all of the fuel assembly designs and operating regions for BWRs. Testing has been performed in the ATLAS facility to demonstrate that the GEXL correlation can be used to predict the onset of boiling transition during postulated transient conditions that are analyzed in the safety analysis process. The ATLAS testing contained data for cosine and inlet peaked axial power shapes. Additional data for inlet and outlet peaked axial power shapes were obtained from the Stern Laboratories Inc. test facility.

The specific GE14 GEXL14 correlation developed for use in the core design and safety analysis process is intended to accurately predict the expected critical power performance of the fuel assembly design. In the core design process, the GEXL14 correlation is used to determine the expected thermal margin for the operating cycle. In the safety analysis process, the GEXL14 correlation is used in the determination of the change in critical power ratio during postulated transients and in the determination of an acceptable MCPR safety limit. Based on the supporting test database, it is concluded that the safety related conditions have been satisfied with respect to the development of an acceptable critical power correlation.

1. INTRODUCTION AND SUMMARY

The GE critical quality - boiling length correlation (GEXL) was developed to accurately predict the onset of boiling transition in boiling water reactor (BWR) fuel assemblies during both steady-state and reactor transient conditions. The GEXL correlation is an integral part of the transient analysis methodology as it is used to confirm the adequacy of the minimum critical power ratio (MCPR) operating limit, and it can be used to determine the time of onset of boiling transition in the analysis of other events.

The GE transient analysis methodology as it is used in the BWR safety analysis process to demonstrate the acceptability of the GE14 reload fuel assembly design is shown in Figure 1-1. The transient analysis methodology is used to perform the required transient analyses which result in establishing the operating limit MCPR and demonstrating conformance to the reactor pressure vessel safety limit. The primary parts of the transient analysis process include: (1) the lattice nuclear design methodology (TGBLA); (2) the three-dimensional BWR simulator (PANACEA); (3) the one- dimensional transient analysis model (ODYN); (4) the steady-state hydraulics and hot channel analysis methodology (ISCOR); (5) the transient critical power calculation methodology (TASC); (6) the fuel rod thermal-mechanical design methodology (GSTRM), and (7) GEXL.

The transient analysis process begins with the use of the lattice physics methods to develop the two-dimensional nuclear libraries which are required as input to the three-dimensional BWR simulator. To perform the required analyses, the lattice physics methods require a fuel assembly description and data from the cross section library to be used. The lattice physics methods also provide the local power distributions used to determine the R-factors for use in the GEXL correlation.

The three-dimensional simulator is used to define the core state and three-dimensional nuclear parameters used as input to the one-dimensional transient analysis model and to establish the fuel rod power histories to be used in the fuel rod design. In addition to the inputs from the lattice physics methods, the three-dimensional simulator requires the reference core loading pattern, core operating state, and the steady-state thermal hydraulic loss coefficients as inputs. These loss coefficients are developed using the steady-state thermal hydraulics methodology and are derived from fuel assembly specific pressure drop data as a function of power and flow. With the GEXL correlation as input, the three-dimensional simulator is used to predict the anticipated MCPR throughout the operating cycle and can also be used in the analysis of slow transients to determine the change in critical power ratio (ΔCPR) for these events.

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Figure 1-1 Transient Analysis Process

ODYN is used to determine the peak transient pressure, the transient change in power, and the transient heat flux and thermal hydraulic parameter changes required as input to both the hot channel analysis and to the transient critical power methodology. The transient peak pressure is used to demonstrate conformance to the reactor pressure vessel safety limit, which is based on the reactor pressure vessel design pressure. The transient change in power is used in the process to demonstrate conformance to the fuel rod plastic strain and centerline melt limits. These limits are developed from the fuel rod design analyses using the fuel rod thermal-mechanical methodology and are based on the fuel physical parameters inputs. The one-dimensional transient analysis methodology collapses the three-dimensional nuclear parameters to one dimension and requires the plant configuration and performance parameters as inputs through the transient base deck.

The hot channel analysis is performed to determine the flow distribution in the core during the transient, and to establish the flow to the limiting channels of each type in the core to be analyzed using the transient critical power methodology. The hot channel analysis is based on the transient parameter changes provided by the one-dimensional transient analysis model. The hot channel analysis requires the axial power shape, local peaking factors, initial critical power ratio (ICPR) which is calculated with the GEXL correlation, and number of fuel assemblies of each type in the core and assembly description for each fuel type as input.

The transient critical power calculational methodology is used to calculate the ΔCPR from the ICPR assumed as an initial condition for the transient being evaluated. This defines the ΔCPR during the transient. The transient critical power calculational methodology requires the GEXL correlation, hot channel hydraulic description, and an assumed ICPR as input.

The CPR calculated during the transient is compared to the safety limit. The MCPR safety limit is established using the GEXL correlation and includes consideration of the operating state and manufacturing uncertainties, and a conservative core power distribution as inputs. If the CPR during the transient exceeds the safety limit, the transient critical power methodology results are used as input to the hot channel analysis to define a new flow distribution for an adjusted ICPR. This process is continued until the results of the transient critical power methodology correspond to the MCPR safety limit. The operating limit MCPR is then the ICPR used for the last iteration.

The GEXL correlation has been used in the safety analysis process for GE fueled BWRs since 1974. The GEXL correlation was developed to provide a best estimate prediction of the onset of boiling transition in BWR fuel assemblies. The GEXL correlation is based on the relationships of critical quality with boiling length; it expresses bundle average critical quality as a function of boiling length, thermal diameter, system pressure, lattice geometry/local peaking pattern (R-factor), mass flux, and annular flow length in later versions of GEXL.

The GEXL correlation was originally developed based on test data typical of 7x7 and 8x8 fuel assemblies. Over 14,000 data points having various numbers of rods, heated lengths, axial heat flux profiles, and rod to rod power distributions were used in the development of the original GEXL (GEXL01) correlation. The boiling transition test data available at the time of the development of the GEXL01 correlation are provided in the original licensing topical report (Reference 1). Further background on the development of the GEXL14 correlation is provided in Section 2.

The GEXL correlation requires the development of coefficients for the specific lattice geometry and peaking factors used in the fuel assembly design. The database supporting the GEXL correlation has been expanded to over 22,000 data points. Of these, over 16,000 points have been obtained using full-scale test assemblies in the ATLAS facility. The database supporting the development of the GEXL14 correlation is described in Sections 3 and 4.

As described above, the GEXL correlation is a critical quality - boiling length correlation. In the GEXL correlation, critical quality is expressed as a function of boiling length, thermal diameter, mass flux, pressure, R-factor, and annular flow length. The axial power profile is not explicitly included in the GEXL correlation. However, the axial power shape is used to calculate boiling length, annular flow length, and axial variation of quality, and thus, is inherently included in the critical power correlation. Since 1974, GE has used only full-scale bundle test data generated in the ATLAS facility for developing the correlation coefficients for new fuel designs. The exact form of the correlation and the coefficients for GE14 fuel are provided in Section 5.

Transient tests simulating turbine trip and all pump trip events are documented in Section 6. Comparison to these tests using a single channel thermal hydraulic code demonstrates the applicability of the GEXL correlation under transient conditions.

The measure of the capability of a boiling transition prediction correlation is its ability to predict the test data. The GEXL correlation has been demonstrated to be an accurate predictor of the available test data. It's capability for predicting GE14 fuel is provided in Sections 4 and 7.

The nomenclature and references used in this report are provided in Sections 9 and 10, respectively.

2. BACKGROUND

One of the general design criteria used in the design of nuclear power plants is that the reactor core and associated coolant, control, and protection systems are to be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences. One of the specified fuel design limits is that there should be a high probability that a fuel rod will not experience the onset of boiling transition, which is frequently referred to in the literature as dryout. The terminology, boiling transition and dryout are considered more descriptive of the phenomenon of interest in fuel design rather than other terms such as critical heat flux, departure from nucleate boiling, or boiling crisis.

Prior to the development of the original GEXL (GEXL01) correlation, a limit line approach was used in the BWR safety analysis process. The limit line was the lower bound in the heat flux versus quality plane for steady-state critical heat flux data. The required operating margin to accommodate anticipated operational occurrences or transients was obtained by maintaining the heat flux at each point in the reactor core no less than a specified distance below the limit line. The figure of merit expressing the required operating margin was the minimum critical heat flux ratio, or the minimum value for the most limiting bundle between the ratio of the limit line heat flux and the operating heat flux, evaluated at the local bundle average quality under given operating conditions.

As the GE BWR boiling transition database was expanded, it was recognized that the use of the local conditions of heat flux and quality to predict critical heat flux had limited applicability. A number of alternative schemes for predicting boiling transition were evaluated. Based on this evaluation, it was determined that boiling transition data were best correlated in the critical quality - boiling length plane. The GEXL01 correlation was developed using this approach. The boiling length is defined as the distance from the point of initiation of bulk boiling to the boiling transition point. Physically, this approach is more realistic for the BWR than a "local condition" hypothesis because, in the annular flow regime present in the high quality region, the boiling transition mechanism depends on gradual depletion of a liquid film covering the fuel rod.

The GEXL14 correlation is a refinement of the original GEXL01 correlation. GEXL14 is based on extensive full-scale critical power tests of GE14 10x10 fuel assembly designs. In addition, the GEXL14 correlation builds on the experience gained from the previous GE11 and GE13 9x9 fuel and GE12 10x10 fuel designs. The GEXL14 correlation maintains the basic form of the GEXL01 correlation with the addition of two new terms. Investigation into two-phase flow and heat transfer mechanisms in the BWR fuel assembly has shown that boiling transition is dependent on annular flow phenomena. Annular flow is the two-phase flow condition where the vapor medium (with entrained liquid droplets) flows in the less obstructed higher velocity regions of the BWR fuel subchannel, while a continuous liquid film flows along the solid surfaces such as the fuel rod, water rod and channel surfaces. The GEXL01 correlation was first modified in the GEXL02 correlation and subsequently in later versions to incorporate the annular flow length parameter.

3. CRITICAL POWER DATABASE

The current GE critical quality-boiling length correlation (GEXL) was developed to provide an accurate means of predicting the occurrence of boiling transition in BWR fuel. The experimental data used in the original development and verification of the GEXL correlation were obtained from three primary sources: (1) reduced length 16 rod bundle steam-water tests conducted at Columbia University; (2) full length 16 rod, 49 rod, and 64 rod bundle tests in the GE Freon loop; and (3) full length 16 rod and full-scale 8x8 lattice tests in the GE ATLAS Heat Transfer Test Facility.

The primary source of boiling transition data used in the development and verification of the GEXL correlation has been generated at the ATLAS facility. The ATLAS test loop creates pressure, flow and temperature conditions that accurately simulate the actual operating reactor environment. Full-scale, electrically heated, simulated reactor fuel bundles are monitored by thermocouples that detect the onset of boiling transition. A more detailed discussion of the ATLAS facility and data collection system and test procedures is provided in Reference 1.

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ATLAS testing was conducted for 10x10 fuel using cosine and inlet peaked axial power shapes. The test bundles contained 78 full length rods, 14 part length rods, and 8 spacers. The GEXL correlations for the 10x10 designs were developed from their respective database. [[

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The GEXL correlations for current fuel designs, including the correlation coefficients and additive constants, are based exclusively on data generated from full-scale tests on prototypical fuel assemblies with the same number of rods and actual fuel assembly geometry. This database includes 8x8 fuel designs with multiple water rods and egg crate spacers typical of the GE8 fuel design, and with a large central water rod and the ferrule spacers typical of the GE9 fuel design. A separate database was used to develop the GEXL07 correlation for the GE11 9x9 fuel design. Exact geometry full-scale tests were performed which included heated part length rods, two large water rods, the interactive channel design with flow trippers, and GE11 ferrule spacer. GE13 is a slightly different version of 9x9 fuel. GEXL09 was developed for this product line based on a full set of GE13 full-scale test data. For the GE12 10x10 fuel, two designs have been evaluated. Geometrically, they are identical except that one design employs an Inconel unit cell spacer, while the other uses a Zircaloy ferrule spacer. Full-scale ATLAS tests for both types of GE12 were performed for the GEXL10 development databases.

GE14 fuel, an improved 10x10 bundle design, uses the GE12 Zircaloy ferrule spacer. [[

]] In Section 5, the final GEXL14 correlation for licensing GE14 fuel is given, including additive constants. The database for GE14 fuel with Zircaloy spacers is summarized in Tables 3-1, 3-3, and 3-4. Table 3-1 shows the cosine database used to develop GEXL14. Tables 3-3 and 3-4 show additional cosine and inlet axial power shape GE14 data collected subsequent to the original GEXL14 development. This additional data further validates the correlation and confirms the axial power shape sensitivity.

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The GE14 test assembly characteristics are provided in Tables 3-2 and 3-5, and Figures 3-1 and 3-2. The tests were performed using a chopped cosine and inlet peaked axial power profile. The axial power profile, for both the full length and part length rods, used in the ATLAS tests are shown in Figures 3-3 and 3-4. [[

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Additional test data were subsequently obtained from the Stern Laboratories Inc.. These tests were obtained for inlet and outlet peaked axial power shapes, and the primary purpose of these tests were to verify the capability of the of the GEXL14 correlation to predict the trend with axial power shape. The database for the Stern Laboratories Inc. GE14 tests [[ ]] is summarized in Tables 3-6 and 3-7. The Stern Laboratories Inc. GE14 test assembly characteristics are provided in Table 3-8 and Figures 3-4 and 3-5.

Table 3-1. GEXL14 Cosine Database for GE14 Fuel with Zircaloy Spacers

Test No.	No. CP Data Points	Dryout Location
[[		
	]]	

Table 3-2. ATLAS GE14 Test Assembly Characteristics

Characteristic	Test Assembly
Test Assembly Number	ATA 751, 756 and 784
Lattice	10x10
Nominal Inside Width of Channel	[[
Corner Radius of Channel	
Channel Wall Feature	
Rod Pitch	
Diameter of All Heated Rods	
Axial Heat Flux Profile of All Full Length Rods	]]
Number of Full Length Heated Rods	78
Heated Length of Full Length Rods	[[ ]]
Number of Heated Part Length Rods	14
Length of Part Length Rods (Heated plus Unheated)	[[
Heated Region of Part Length Rods	]]
Number of Water Rods	2
Diameter of Large Water Rods	[[ ]]
Number of Spacers on the Heated Length	8
Spacer Type	Zircaloy ferrule
Nominal Elevations of Spacer Leading Edge Relative to the Full Length Rod Beginning of the Heated Length:	
8	[[
7	
6	
5	
4	
3	
2	
1	]]
Hydraulic Parameters Used in GEXL Correlation:	
Flow Area	[[
Hydraulic Diameter	
Thermal Diameter	]]

Table 3-3. Additional Cosine Database for GE14 Fuel with Zircaloy Spacers

Test No.	Number of Critical Power Data Points	Dryout Location
[[		
	]]	

Table 3-4. Additional Inlet Peaked Database for GE14 Fuel with Zircaloy Spacers

Test No.	Number of Critical Power Data Points	Dryout Location
[[		
	]]	

Table 3-5. ATLAS GE14 Test Assembly Characteristics for Additional GE14 Data

Characteristic	Test Assembly
Test Assembly Number	ATA 964, 966, 971, 975, 977, 983, 984
Lattice	10x10
Nominal Inside Width of Channel	[[
Corner Radius of Channel	
Channel Wall Feature	
Rod Pitch	
Diameter of All Heated Rods	
Axial Heat Flux Profiles (2) of All Full Length Rods	]]
Number of Full Length Heated Rods	78
Heated Length of Full Length Rods	[[ ]]
Number of Heated Part Length Rods	14
Length of Part Length Rods (Heated plus Unheated)	[[
Heated Region of Part Length Rods	]]
Number of Water Rods	2
Diameter of Large Water Rods	[[ ]]
Number of Spacers on the Heated Length	8
Spacer Type	Zircaloy ferrule
Nominal Elevations of Spacer Leading Edge Relative to the Full Length Rod Beginning of the Heated Length:	
8	[[
7	
6	
5	
4	
3	
2	
1	]]
Hydraulic Parameters Used in GEXL Correlation:	
Flow Area	[[
Hydraulic Diameter	
Thermal Diameter	]]

Table 3-6. Additional Stern Laboratories Inc. Inlet Peaked Database for GE14 Fuel with Zircaloy Spacers

Test No.	Number of Critical Power Data Points	Dryout Location
[[		
	]]	

Table 3-7. Additional Stern Laboratories Inc. Outlet Peaked Database for GE14 Fuel with Zircaloy Spacers

Test No.	Number of Critical Power Data Points	Dryout Location
[[		
	]]	

Table 3-8. Stern Laboratories Inc. GE14 Test Assembly Characteristics for Additional GE14 Data

Characteristic	Test Assembly
Test Assembly	Bottom and Top Peaked APS
Lattice	10x10
Nominal Inside Width of Channel	[[
Corner Radius of Channel	
Channel Wall Feature	
Rod Pitch	
Diameter of All Heated Rods	
Axial Heat Flux Profiles (2) of All Full Length Rods	
	]]
Number of Full Length Heated Rods	78
Heated Length of Full Length Rods	[[ ]]
Number of Heated Part Length Rods	14
Length of Part Length Rods (Heated plus Unheated)	[[
Heated Region of Part Length Rods	]]
Number of Water Rods	2
Diameter of Large Water Rods	[[ ]]
Number of Spacers on the Heated Length	8
Spacer Type	Zircaloy ferrule
Nominal Elevations of Spacer Leading Edge Relative to the Full Length Rod Beginning of the Heated Length:	
8	[[
7	
6	
5	
4	
3	
2	
1	]]
Hydraulic Parameters Used in GEXL Correlation:	
Flow Area	[[
Hydraulic Diameter	
Thermal Diameter	]]

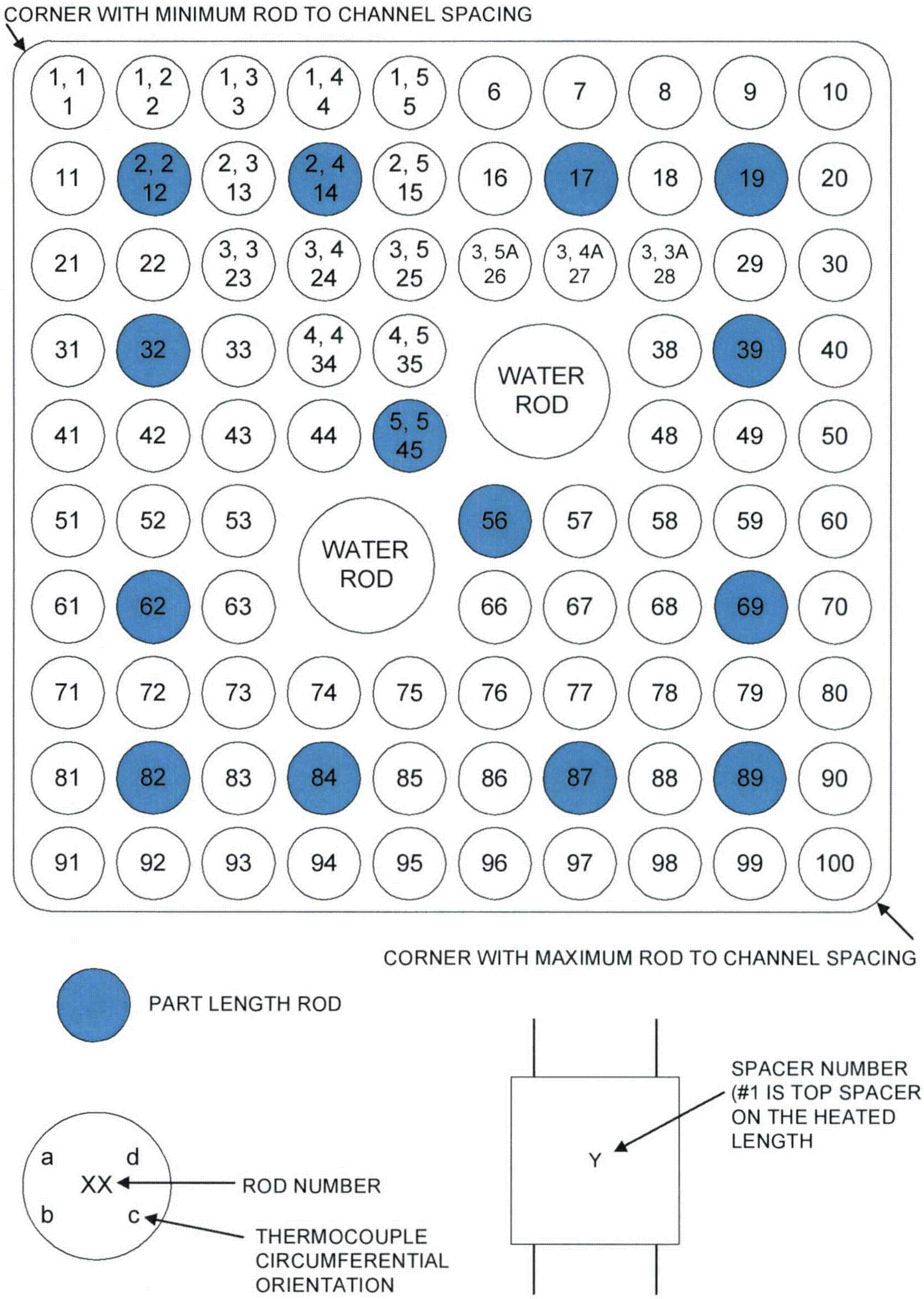

Figure 3-1. GE14 Test Assembly Rod Numbering System and Thermocouple Location

[[

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Figure 3-2. Typical Rod Axial Heat Shape - ATLAS Critical Power Tests

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Figure 3-3. Typical Bundle Axial Heat Shape - ATLAS Critical Power Tests

[[

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Figure 3-4. Typical Rod Axial Heat Shape – Stern Laboratories Inc. Critical Power Tests

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Figure 3-5. Typical Bundle Axial Heat Shape – Stern Laboratories Inc. Critical Power Tests

4. TEST MATRIX AND CORRELATION PROCEDURES

4.1 INTRODUCTION

The GE14 10x10 fuel design is an evolutionary product based on the experience gained in the GE9/10 8x8, the GE11/13 9x9 and GE12 10x10 fuel designs. In each case, critical power performance estimates and ATLAS test matrix procedures have been derived from the results obtained with previous tests. In the GE9/10 fuel designs, cosine and inlet peaked power distributions were included in the critical power test matrix. When the part length rod design feature was added to the 9x9 GE11/13 fuel designs, outlet peak power distributions were added to the test matrix.

The COBRAG (Reference 2) subchannel computer program has been extensively qualified against a large amount of critical power data and has been successful in predicting differences between axial power shapes as well as differences between 8x8, 9x9 and 10x10 lattice configurations. The large amount of critical power data collected in the GE9/10, GE11/13 and GE12 tests and the success of the COBRAG subchannel computer model in predicting these data allow the use of COBRAG calculations to benchmark the GEXL correlation. Appendix A summarizes the COBRAG qualification and the comparisons between data, COBRAG calculations, and the GEXL correlation.

4.2 THE GE14 10X10 TEST MATRIX

The GE14 10x10 ATLAS test matrices are outlined in Table 4-1 and 4-2. [[

]]

1) Over 1800 test points were acquired using the inlet, outlet and cosine power distributions in the GE11 and GE13 test series. These tests provide an extensive database for the formulation of the GEXL coefficients which simulate axial shape effects. This extensive experience has been previously applied to the generation of the GEXL10 correlation. It can also be applied to the GEXL14 correlation development.

2) Additional cosine and inlet power distribution GE14 data generated in the ATLAS facility subsequent to the original GEXL14 development validates the axial power shape effects and has demonstrated that the axial power shape effect is well predicted by GEXL14.

3) Additional inlet and outlet peaked axial power distribution GE14 data generated in the Stern Laboratories Inc. facility subsequent to the original GEXL14 development and validation provides further validation that the axial power shape effect is well predicted by GEXL14. The Stern Laboratories Inc. test matrix is outlined in Table 4-2A. [[

]]

4) Additional benchmarking against COBRAG calculations is contained in Appendix A.

Table 4-1. GE14 ATLAS Test Matrix Critical Power (Steady-state)

Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	[[
Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	
Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	
Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	]]

Table 4-1. GE14 ATLAS Test Matrix Critical Power (Steady-state), continued

Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	[[
Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	]]

Table 4-2. GE14 ATLAS Test Matrix for Additional Data Collection (Steady-state)

Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	[[
Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	
Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	
Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	
Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	]]

Table 4-2. GE14 ATLAS Test Matrix for Additional Data Collection (Steady-state) (continued)

Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	[[
Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	]]

Table 4-2A. GE14 Stern Laboratories Inc. Test Matrix for Additional Data Collection (Steady-state)

Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	[[
Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	
Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	
Test Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet subcooling:	]]

4.3 CORRELATION PROCEDURE FOR GEXL14

The procedure used for the GEXL14 correlation can be summarized as follows:

- A range of test data covering all parameter variations was selected to form a development database. This is the majority of the test data. A number of tests were repeated during the testing to verify reproducibility of the test data. These tests were used as the verification database.
- The GEXL correlation was fit to the ATLAS data and optimized to minimize the bias and standard deviation in correlating the data.
- Once the optimum coefficients are determined, the apparent R-factors are calculated for each test assembly. The apparent R-factor is defined as that R-factor which yields an overall ECPR (ratio of calculated to measured critical power) of 1.0 for a given assembly.
- Finally the additive constants are determined by calculating the maximum R-factor for each assembly and adjusting the additive constants such that the difference between the assembly R-factor and the apparent R-factor is minimized.

[[

]] Additional 8x8 data were not required. The GETAB SER contains the following statement about such additional data: "Although these tests can provide additional confirmation of the 8x8 GEXL correlation predictive capability, they are not required for two reasons. First, the 7x7 GEXL correlation, which was based solely on data from uniform and cosine axial heat flux profile tests, accurately predicts boiling transition for the other tested profiles. There is no reason to believe that the 8x8 GEXL correlation would not perform similarily. Second, in the application of GEXL, the standard deviation of the uncertainty in the 8x8 GEXL correlation will be increased to account for the less complete data base. The standard deviation of 2700 experimental critical power ratios (ECPR) about the 7x7 GEXL correlation is 3.6%. The standard deviation of 1299 ECPR about the 8X8 GEXL is 2.8%. In applying the 8X8 GEXL to the determination of the BWR thermal limits, the standard deviation will be increased to at least 3.4%, which is the square root of the sum of the variance of the 8X8 experimental results and the variance of the means of the 7x7 data for each flux shape". These two requirements can be applied to the 9x9 and 10x10 GEXL correlation. [[

]] Therefore the first requirement is satisfied. [[

]] Therefore the second requirement of the GETAB SER is also satisfied.

- Benchmarking against COBRAG provided an independent check on the axial power shape effect (see Appendix A).

These steps were taken to optimize GEXL14 for the GE14 product line, minimize the prediction uncertainty and ensure that the axial power shape effects were accurately accounted for.

4.4 TEST CORRELATION

The GE14 GEXL correlation is denoted GEXL14 and its coefficients are compared to the GEXL10 and GEXL07 correlation in Table 4-3. Note that all of the coefficients are very similar except the first four, which give the mass flux dependence. The effectiveness of the thermal hydraulic design will influence the mass flux behavior of the correlation. The more efficient the critical power design, the greater the sensitivity to mass flux. This behavior is due to the fact that at low mass flux, most designs have the same critical power because the critical power behavior is governed by pool boiling phenomena. At higher mass flux, the more efficient designs have higher critical power and the gain in critical power is larger. For this reason, the flow dependence often has to be re-optimized when a new lattice design is initiated. [[

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[[

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Table 4-3. GEXL14, GEXL10 and GEXL07 Correlation Coefficients

		A(I)		
I	V(I)	GEXL14	GEXL10	GEXL07
1	[[			
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				]]

D_Q Thermal diameter, in.
G Mass flux, Mlb/ft^2-hour.
L_B Boiling length, in.
L_A Annular length, in.
P Pressure, psia.
R Rod R-factor.

Table 4-4. Statistical Summary for GEXL14

Zircaloy Spacer	Correlation Database	Development Database	Verification Database
Number of Data Points	[[		
Mean ECPR			
Standard Deviation, σ (%)			]]

Table 4-5. Statistical Summary for Additional GE14 Data

Zircaloy Spacer	Correlation Database	Cosine Data	Inlet Data
Additional Data Points	[[		
Mean ECPR			
Standard Deviation, σ (%)			]]

The additive constants derived for the GEXL14 correlation are described in detail in Section 5. In order to compare the relative performance of the GE14 design with the GE12 design, one can compare both the additive constants and the GEXL correlation prediction. Given the same flow conditions and R-factor, GEXL10 and GEXL14 predict similar critical powers. The relative critical power efficiency at each fuel rod position can then be compared by using the R-factor or additive constants difference. Table 4-6 presents such a comparison, giving the average additive constants for the outer rod row, second row, etc. The results in Table 4-6 also show the magnitude of the additive constants difference which can be translated into a performance enhancement of GE14 over GE12. [[

]]

Table 4-6. Comparison of GE14 and GE12 Additive Constants

		Average Additive Constants		
Full Length Rod Position	Number of Positions	GE14	GE12 with Inconel spacer	GE12 with Zircaloy spacer
Corner rod	[[			
Outer row				
Second row				
Central				]]

4.5 AXIAL POWER SHAPE EFFECT

The GEXL14 axial power shape effects were evaluated using the GE14 cosine and inlet peaked power shape data and through trend comparisons of 9x9 and 10x10 fuel designs. The comparisons show that GEXL14 power shape effects are well predicted compared to ATLAS data and consistent with the trend observed in previous fuel designs. Based on these evaluations, a conservative correlation uncertainty was determined using the previously approved methods from GETAB (Reference 1).

4.6 GEXL14 CORRELATION STATISTICS

The GETAB process defines the mean and standard deviation of the GEXL correlation be given by:

$$\overline{ECPR} = \frac{1}{n}\sum_{i=1}^{n} ECPR_i \qquad \sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(ECPR_i - \overline{ECPR})^2} \qquad (4\text{-}1)\ (4\text{-}2)$$

If the data consist of m sets of data, e.g., m different axial power shapes, correlation statistics can be developed for each set:

$$\overline{ECPR_j} = \frac{1}{n_j}\sum_{i=1}^{n_j} ECPR_i \qquad \sigma_j = \sqrt{\frac{1}{n_j-1}\sum_{i=1}^{n_j}(ECPR_i - \overline{ECPR_j})^2} \qquad (4\text{-}3)\ (4\text{-}4)$$

where the summation is over the data in set j.

The following relation exists:

$$\overline{ECPR} = \frac{\sum_{j=1}^{m} n_j \overline{ECPR_j}}{\sum_{j=1}^{m} n_j} \qquad \sigma^2 = \frac{\sum_{j=1}^{m}(n_j-1)\sigma_j^2}{\sum_{j=1}^{m} n_j - 1} + \frac{\sum_{j=1}^{m} n_j(\overline{ECPR}_j^2 - \overline{ECPR}^2)}{\sum_{j=1}^{m} n_j - 1} \qquad (4\text{-}5)\ (4\text{-}6)$$

[[

]]

Table 4-7. 9x9 and 10x10 Axial Power Shape Sensitivities

Power Shape	9x9 Fuel				10x10 Fuel	
	GE11 (GEXL07)		GE13 (GEXL09)		GE14 (GEXL14)	
	ECPR	σ (%)	ECPR	σ (%)	ECPR*	σ (%)*
Inlet	[[					
Cosine						
Outlet						
Total [# of Points]						
Variance of means						]]

[[

]]

From the GE14 data and from the past databases the following data were evaluated and calculation results are shown in Table 4-8:

Table 4-8. Historical Uncertainty Adders

Fuel Type	σ_1	σ_2
[[		
		]]

The σ_1 and σ_2 values obtained from the GE11 data were determined to be bounding and were used in the evaluation of the bias and uncertainty for the GEXL14 correlation. Consistent with the GETAB process used for 8x8 fuel, the bias (ECPR) for the GEXL14 correlation is based on cosine data and the impact on the bias due to power shape is accounted for by increasing the uncertainty (σ) as show above. The final correlation bias and uncertainty are shown in Table 4-9.

Table 4-9. GEXL14 Correlation Bias and Uncertainty

	[[	
Number of data points		
Mean ECPR		
Standard deviation, σ (%)		]]

4.7 POWER SHAPE SENSITIVITY COMPARISON

[[

]]

[[

]]

Figure 4-1. Power Shape Sensitivity Comparison for 9x9 and 10x10 Fuel Designs

[[

]]

The statistics for the validation of the GEXL14 correlation against the Stern Laboratories Inc. data is given in the Table 4-10:

Table 4-10. GEXL14 Compared to Stern Laboratories Inc. Data

	Bottom Peaked Axial Power Shape	Top Peaked Axial Power Shape	All Data
Number of Data Points	[[		
Mean ECPR, μ			
Standard Deviation			]]

[[

]]

Additional benchmarking against the COBRAG subchannel code in Appendix A provides further confirmation of the conservatism in the correlation uncertainty.

4.8 HIGH R-FACTOR

[[

]]

4.9 PRESSURE RANGE

[[

]]

4.10 CONCLUSION

The GEXL14 correlation has been validated against ATLAS data for cosine and inlet peaked axial power shapes and against Stern Laboratories Inc. data for inlet and outlet peaked axial power shapes. These comparisons show that the axial power shape sensitivity is well predicted by the GEXL correlation. [[

]]

5. CRITICAL POWER CORRELATION

5.1 FORM OF THE GEXL CORRELATION

As discussed in Section 2, the critical quality versus boiling length plane was chosen by GE as the coordinate system for correlating the boiling transition data described in Section 3. This approach was chosen because (1) it yields good precision, (2) is conceptually simple to apply, and (3) will account for variations in axial heat flux profile. The critical quality - boiling length correlation developed to predict the critical power in BWR fuel assemblies is called GEXL.

The GEXL correlation, expressed in the most general terms, is:

$$X_C = f(L_B, D_Q, G, P, R, L_A) \tag{5-1}$$

where:

X_C = Critical quality (dimensionless)
L_B = Boiling length (in.)
D_Q = Thermal Diameter (in.)
G = Mass flux (10^6 lb/hr-ft^2)
P = Pressure (psia)
R = R-factor (dimensionless)
L_A = Annular flow length (in.)

Because GEXL is a dimensional correlation the above units must be used in specific analyses.

The explicit form of the GEXL correlation is:

$$X_C = \sum_{I=1}^{18} A(I) \cdot V(I) \tag{5-2}$$

where the correlation parameters, V(I), and the coefficients, A(I), are shown in Table 4-2 and are repeated on the next page for the convenience of the reader.

I	V(I)	A(I)
1	[[	
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		]]

5.2 GEXL14 APPLICATION RANGE

The GEXL14 correlation for GE14 fuel is valid over the range stated below:

Pressure:	4.8 to 9.7 MPa (700 to 1400 psia)
Mass Flux:	*136 to 2448 kg/sec-m^2 (0.1 x 10^6 to 1.8 x 10^6 lb/hr-ft^2)
Inlet Subcooling:	0 to 233 kJ/kg (0 to 100 Btu/lb)
R-factor:	*0.9 - 1.25
*exception	in R-factor and Mass flux plane, the parameters should also satisfy: (1.2-R)/0.05 ≥ (G-1.5)/0.3 for 1.15 < R < 1.20 (1.25-R)/0.05 ≥ (G-1.3)/0.2 for 1.20 < R < 1.25 The upper mass flux range for R < 1.15 is 2448 kg/sec-m^2

[[

]]

5.3 CALCULATION OF CRITICAL POWER BY GEXL

For steady-state conditions, critical power is predicted by an iterative procedure. Given the pressure, flow rate, inlet subcooling, axial power shape, and fuel lattice design and an assumed value for the critical power, local quality and boiling length are computed for each axial node (generally 24 or 25 nodes are assumed) using energy and mass balance relationships. The critical quality is also computed for each node using Equation 5-2. If, at any of the nodes, the local quality is greater than the critical quality, a lesser value for the critical power is assumed. If the local quality is less than the critical quality at all of the nodes, a greater value for the critical power is assumed. The iteration continues until the local quality is just equal to the critical quality at one of the nodes and is less at all other nodes. The power for this last iteration is the predicted critical power.

This process is illustrated in Figure 5-1 where the dashed/solid lines show the critical and equilibrium quality profiles for the first and last iterations. The equilibrium quality X is a function of bundle elevation z and is calculated from:

$$X(z)=\left[Q(z)/W-(h_f-h_{in})\right]/(h_g-h_f) \tag{5-3}$$

In Equation 5-3, X = local quality; z = axial coordinate for elevation in the bundle; Q = integrated power input to the coolant up to location z; W = bundle coolant flow rate; h_f = saturated liquid enthalpy; h_{in} = inlet liquid coolant enthalpy; and h_g = saturated vapor enthalpy.

For design application the correlation is intended to iteratively determine the bundle power which satisfies the requirement that for some z, $X = X_C$ and $X < X_C$ for all other z. It also should be noted that the values of X_C, X and z at which (X_C - X) is a minimum, change with each iteration on bundle power.

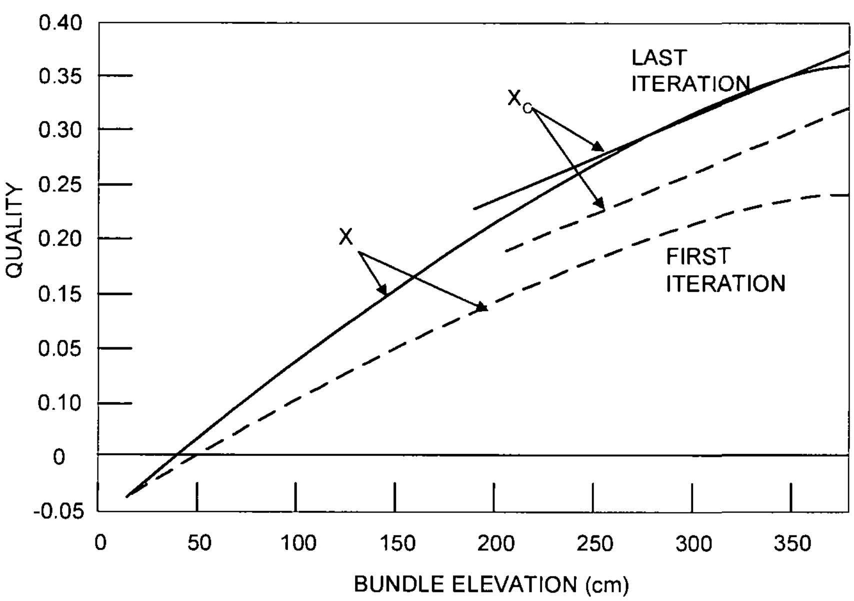

Figure 5-1. GEXL Critical Power Iteration Scheme

The critical power ratio (CPR) is the ratio of the predicted critical power to the actual power of the particular fuel assembly, both evaluated at the same pressure, mass flux, and inlet subcooling. The minimum critical power ratio (MCPR) is defined as the minimum CPR for any fuel assembly within a core and is the figure of merit to represent the reactor thermal performance or margin.

GEXL is also applied under transient conditions within the parameter ranges specified in Section 5.2. GEXL is used under transient conditions in the similar manner as it is used under steady-state conditions described above.

5.4 GEXL INPUT PARAMETERS

This section describes the necessary inputs to the GEXL correlation for the bundle critical power calculation. Based on Equation 5-1, there are six input parameters required for the calculation of critical power. These parameters are: (1) boiling length, L_B; (2) thermal diameter, D_Q; (3) mass flux, G; (4) pressure, P; (5) bundle R-factor, R; and (6) annular flow length, L_A. These parameters are discussed in more detail below.

5.4.1 Boiling Length

Boiling length, L_B, is the distance from the onset of thermodynamic average bulk boiling to the point of boiling transition. Boiling length is not a direct input to GEXL, but it is calculated through the energy balance during the calculation of critical power described in Section 5.3. The boiling length is dependent on the core pressure, enthalpy at the fuel assembly inlet, normalized axial power shape, mass flux, and bundle power level.

5.4.2 Thermal Diameter

The thermal diameter, D_Q, is a characteristic diameter defined in the fully rodded region as four times the bundle active coolant flow area divided by the total rodded perimeter including any water rods. The rodded perimeter does not include the channel. The thermal diameter used in the GEXL14 correlation for GE14 fuel is [[ ]], and the flow area is [[ ]]. Both parameters are assumed to be constant over the length of the fuel assembly.

5.4.3 Mass Flux

The mass flux, G, is defined as the bundle active coolant flow per unit flow area in the fully rodded region.

5.4.4 Pressure

The pressure, P, is defined as the system pressure and taken as the core pressure at the end of the total active fuel length and assumed constant throughout the bundle.

5.4.5 R-Factor

The R-factor is a parameter which accounts for the effects of the fuel rod power distributions and the fuel assembly local spacer and lattice critical power characteristics. Its formulation for a given fuel rod location depends on the power of that fuel rod, as well as the power of the surrounding fuel rods. A detailed description of the R-factor calculation method is provided in Section 8. In addition, there is an additive constant applied to each fuel rod location [[

]] For GE14, the additive constants used in the design process are provided in Table 5-1.

Table 5-1. GEXL14 Additive Constants for GE14 with Ferrule Spacer

Fuel Rod Lattice Position	Fuel Rod Additive Constant
[[	
	]]

*Part length fuel rods
**For rods not adjacent to a water rod
***For rods adjacent to a water rod (refer to Figure 8-3 in Section 8)

5.4.6 Annular Flow Length

Annular flow length, L_A, is defined as the distance from the slug/annular flow transition point to the point of boiling transition. Investigation into two-phase flow and heat transfer mechanisms in a BWR fuel bundle has shown that boiling transition depends on the annular flow phenomenon. This conclusion was reached based on an improved understanding of the boiling transition phenomena for BWRs supported by the experience gained during ATLAS testing.

Annular flow is the two-phase flow condition where the vapor medium (with entrained liquid droplets) flows in the less obstructed higher velocity regions of the BWR fuel subchannel, while a continuous liquid film flows along the fuel rod, water rod, and channel surfaces. Boiling transition occurs in the annular flow regime when the thin liquid film covering the fuel rod ruptures. Use of the annular flow length parameter improved the accuracy of the critical quality-boiling length correlation, by providing a parameter that can more directly characterize the complex liquid vaporization, film entrainment, and droplet deposition mechanisms. ATLAS test data has indicated that the importance of the annular flow term in the GEXL correlation may be dependent on fuel assembly design.

[[

]]

Figure 5-2 provides a representation of two-phase flow regimes in a heated cylindrical tube. Boiling transition occurs at the point of disruption or complete depletion of the liquid film layer on a heated fuel rod surface. The slug to annular flow transition point is characterized by the transition from the state of vapor entrainment in a continuous liquid phase flow medium to a state of liquid entrainment in a continuous vapor phase flow medium. The location of transition to annular flow, $Z_{TR} = Z(X{=}X_{TR})$, is determined from the [[ ]] given by Equation 5-4:

[[ ]] (5-4)

where j_g^* and j_f^* are the dimensionless vapor and liquid velocities and are defined by:

$$j_g^* = G_g\ (\rho_g)^{-1/2}\ [(gD_H)\ (\rho_f - \rho_g)]^{-1/2} \tag{5-5}$$

$$j_f^* = G_f\ (\rho_f)^{-1/2}\ [(gD_H)\ (\rho_f - \rho_g)]^{-1/2} \tag{5-6}$$

and where D_H is the hydraulic diameter of the fully rodded region,

$$G_g = XG \tag{5-7}$$

$$G_f = (1 - X)\ G \tag{5-8}$$

Combining these expressions gives the annular flow transition quality

[[ ]] (5-9)

Thus the annular flow length is given by

[[ ]] (5-10)

where

$$Z_{TR} = Z \quad \text{when } X = X_{TR}\ . \tag{5-11}$$

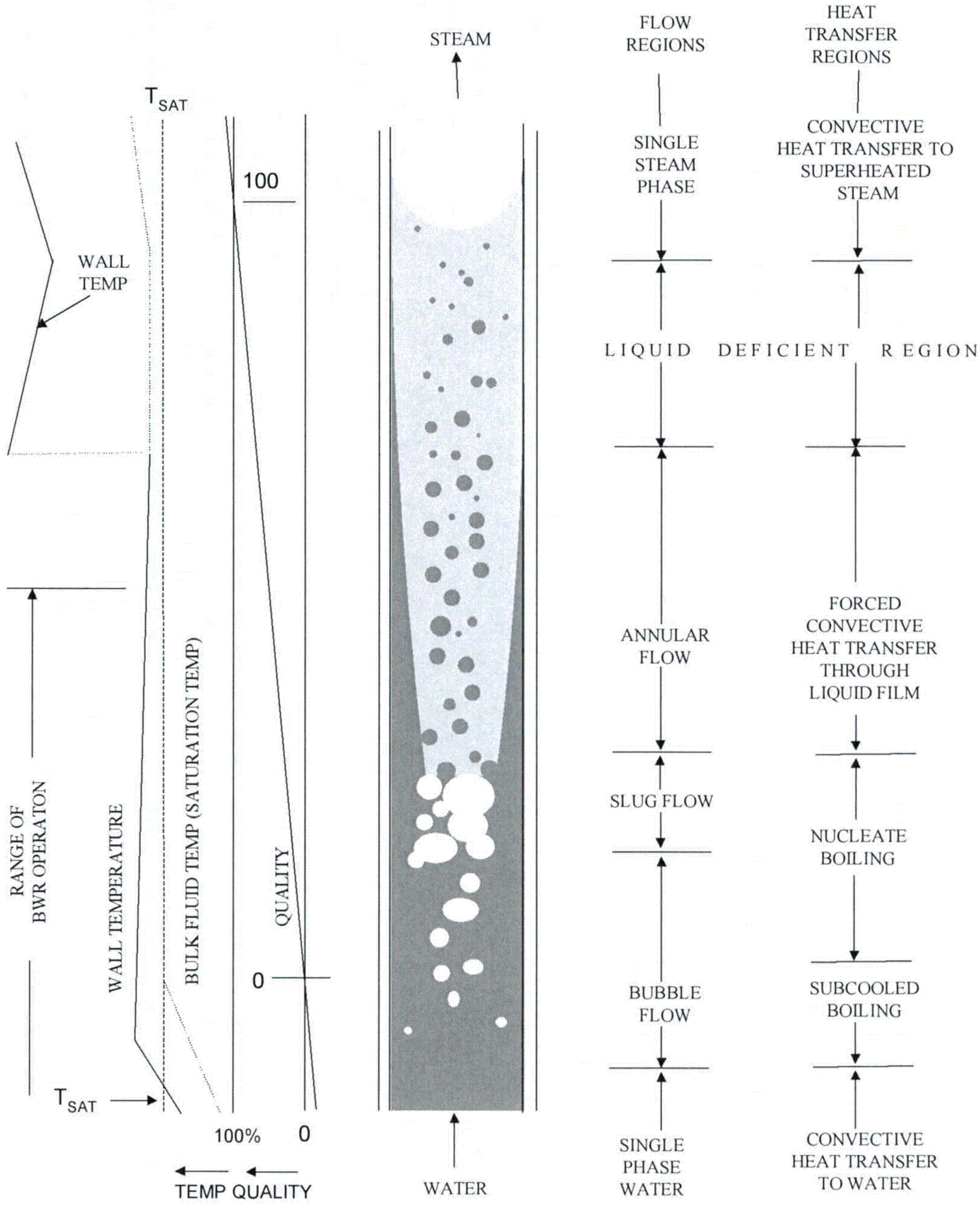

Figure 5-2. Regimes of Two-Phase Flow

5.5 GEXL CORRELATION INTERFACES

As described in Section 1, GEXL interfaces with the core design and transient analysis process in four places: (1) the core nuclear design and management process through the three-dimensional BWR simulator; (2) initialization of the CPR for the hot channel analysis; (3) the transient change in CPR calculation through the TASC code; and (4) the determination of the MCPR safety limit. The following describes the use of the GEXL correlation, with emphasis on the R-factor effects, in core nuclear design and management, in the transient analysis process, and in the determination of the MCPR safety limit.

The GEXL correlation is used in the core nuclear design and management process to predict the CPR for all fuel assemblies in the core throughout the operating cycle. The CPR is dependent on the fuel assembly R-factor. Bundle R-factors are calculated as a function of bundle average exposure, for each bundle design. For a partially controlled bundle, these calculations provide sufficient information to calculate the bundle R-factor for any given control fraction.

In the transient analysis, the thermal margin change during the event (ΔCPR) is determined using the GEXL correlation, which is the difference between the initial (steady-state) MCPR and the lowest MCPR during a transient. The steady-state operating limit MCPR is the summation of the maximum |ΔCPR| to the minimum allowable CPR during the transient (the safety limit MCPR).

There are two types of transients required to be analyzed for ΔCPR values, (1) plant (core wide) transients, such as the turbine trip, and (2) localized events such as the rod withdrawal error (RWE) occurring during power operation.

The R-factors used in the transient ΔCPR calculation for core wide transients are dependent on the fuel assembly type. The transient ΔCPR calculation is very insensitive to the R-factor used. For the Rod Withdrawal Error (RWE), the R-factor used in analysis is identical to the one used in the nuclear core design and management process described above.

The safety limit MCPR is dependent on the fuel and reactor parameters and their uncertainties. It is selected such that a very high percentage of the fuel rods in the core would be expected to avoid boiling transition. The value for the safety limit MCPR is determined through a statistical analysis considering the uncertainties in the GEXL correlation, the plant instrumentation system for measuring operating parameters (feedwater flow, feedwater temperature, reactor pressure, core inlet temperature, core flow), and the plant process computer for determining core power level and distribution.

6. TRANSIENT QUALIFICATION

Changes in critical power during an operational transient are calculated with a single channel two-phase transient thermal hydraulic model. The single channel thermal hydraulic program solves the heat conduction equation for the fuel rods and the conservation equations for mass, momentum and energy for the fluid. The GEXL14 correlation is used together with the transient thermal hydraulic conditions computed by the single channel program to compute the change in CPR during a given transient. The qualification of GEXL14 is accomplished by comparing the change in critical power ratio with experimental results obtained from the ATLAS thermal hydraulic test facility.

In addition to measuring steady state critical power, the ATLAS facility is capable of determining critical power or dryout conditions under transient conditions. Transient conditions are generated by varying the inlet flow, pressure, and bundle power as a function of time. For simulation of a turbine trip event, the flow is held constant and then decreased shortly after the beginning of the event. The bundle power is increased and then decreased to simulate the heat flux. The pressure is rapidly increased by opening the valve between the pressurizer and the flow loop at the appropriate time. A typical turbine trip transient input is shown in Figure 6-1. Also shown are temperature traces from several thermocouples. Note the temperature rise in one of the thermocouples, indicating a degradation of heat transfer capability and critical power condition.

[[

]] (6-1)

For the GEXL14 correlation, three transient tests were performed. The experimental conditions are summarized in Table 6-1.

Table 6-1. Summary of GEXL14 Transient Tests

Transient Test Type	Initial Flow kg/sec-m^2 (Mlb/ft^2 hr)	Inlet Subcooling kJ/kg (Btu/lb)	Pressure MPa (psi)	Integrated Power Increase (%)
ALL Pump Trip	[[			
TTNBP/NRPT				
TTNBP/RPT				]]

A comparison of calculated versus measured results is summarized in Figure 6-2 along with a comparison of GEXL10 and GE12 transient data. These results show that the GEXL14 correlation duplicates the transient ΔCPR/ICPR within [[

]]

[[

]]

Figure 6-1. Transient Test Response for a Turbine Trip with Pump Trip Transient

[[

]]

Figure 6-2. Summary of Transient ΔCPR/ICPR Comparison

7. GE14 CRITICAL POWER TEST EVALUATION

The GE critical quality-boiling length correlation (GEXL) was developed to be an accurate, best estimate predictor of boiling transition in BWR fuel. A large critical power test database was obtained as part of the development of the GEXL correlation. The data covered the full range of BWR steady-state operating and transient conditions for which an accurate prediction of critical power is an important element of the safety analysis process. GEXL has an excellent predictive capability as demonstrated by the comparisons to the steady-state critical power data obtained during the development work described in Reference 1. The ability of the GEXL correlation to accurately predict the critical power performance of BWR fuel is demonstrated by the comparisons in Reference 1 which show that, for recent fuel designs, the uncertainty of critical power estimates using GEXL is approximately [[ ]]. Also, the data demonstrates that GEXL can be used to predict critical power under BWR transient conditions.

The GEXL14 correlation was developed from data obtained in full-scale critical power simulations of GE14 10x10 fuel assemblies having reactor grade spacers. Test data obtained for 8x8 and 9x9 fuel assemblies with ferrule spacers and large central water rods, and developmental testing of a GE14 lattice configuration also were of particular importance in establishing a GE14 GEXL correlation. This section provides the results of analyses performed to demonstrate the application of the final GE14 GEXL14 correlation to predict the GE14 test data.

A statistical analysis was performed for the GE14 database consisting of [[ ]] different local peaking patterns obtained from the ATLAS test assembly. The data and analyses cover the range for which the GE14 GEXL14 correlation is considered valid, as identified in Section 5. To facilitate the statistical evaluation of the predictive capability of the GE14 GEXL14 correlation, the concept of an experimental critical power ratio (ECPR) is used. The ECPR is determined from the following relationship:

$$ECPR \equiv \frac{\text{PredictedCriticalPower}}{\text{MeasuredCriticalPower}} \tag{7-1}$$

Figure 7-1 shows the frequency distribution of all ECPRs for GEXL versus test data results for GE14 with Zircaloy spacers. The frequency distribution is statistically confirmed as a normal distribution. Figure 7-2 shows the frequency distribution of the additional data generated for GE14 from the ATLAS facility for cosine and inlet axial power shapes. A simple visual statistical comparison (Figure 7-3) of the two sets of ATLAS data show that they have similar means (indicated by red lines) and similar populations. The difference in the means is small when compared to the ATLAS reproducibility capability and measurement accuracy. The combined statistics for the GEXL14 correlation of the original and additional data [[

]]

In summary, critical power data recorded under simulated reactor operating conditions with GE14 test assemblies have been fitted to the GEXL correlation. This best estimate fit accurately predicts the onset of boiling transition for typical expected steady-state and transient conditions. The overall prediction errors follow a normal distribution.

[[

]]

Figure 7-1. Frequency versus ECPR Histogram for GE14 ATLAS Data (Cosine)

[[

]]

Figure 7-2. Frequency versus ECPR Histogram for GE14 Additional ATLAS Data (Cosine and Inlet Peaked)

[[

]]

Figure 7-3. Comparison of Database Populations and Mean ECPR

8. R-FACTOR CALCULATION METHOD

8.1 INTRODUCTION

The R-factor is an input to the GEXL correlations that accounts for the effects of the fuel rod power distributions and the fuel assembly and channel geometry on the fuel assembly critical power. Its formulation for a given fuel rod location depends on the power of that fuel rod, as well as the power of the surrounding fuel rods. In addition, there is an additive constant applied to each fuel rod location that is dependent on the fuel assembly and channel geometry.

A change in R–factor calculation method was necessitated by the addition of part length rods in GE11 and later product lines. The new methodology (Reference 4), which includes the use of the COBRAG subchannel code (Reference 2) specifically for controlled part length rod R-factor calculations, was submitted to the NRC and accepted (Reference 5) as part of the GE reload licensing application.

The capability of the GEXL14 correlation to predict the ATLAS data demonstrates the applicability of the R-factor method for GE14 fuel as required by the NRC Safety Evaluation Report to the R-Factor Methodology Licensing Topical Report (Reference 5). This evaluation is based on correlation statistics and the trend characteristics of the GEXL14 correlation relative to the GEXL correlations for GE11, GE12 and GE13 fuel. It demonstrates that the GE14 characteristics are predicted as well as those for previous fuel types.

8.2 R-FACTOR CALCULATIONAL PROCESS

Local two-dimensional fuel rod power distributions vary axially in BWR fuel assemblies due to axial variations in nuclear design, exposure, void fraction and control state. These factors are considered when calculating the axially integrated powers for individual rods. The two-dimensional distribution of integrated rod powers for a bundle is then used to calculate individual rod R-factors. The bundle R-factor for a particular bundle average exposure and control fraction is the maximum of all of the individual fuel rod R-factors. The steps used in the R-factor calculational process are as follows:

1. Obtain relative 2D rod-by-rod power distributions from TGBLA, which are a function of lattice nuclear design, average exposure, void fraction and control state.
2. [[

   ]]
3. Calculate an R-factor for each individual fuel rod. [[

   ]]
4. The bundle R-factor is the maximum value of all the individual rod R-factors.
5. Repeat these calculations for each desired bundle average exposure, control fraction and channel bow.

8.3 BUNDLE AVERAGE AXIAL DISTRIBUTIONS

A 25-node axial shape is used to define a bundle axial relative power shape for the purposes of calculating R-factors. This shape is a function of control fraction. Bundle axial void fraction and bundle axial relative exposure shapes are used to determine two-dimensional radial distributions as a function of axial height.

[[

]]

- The **bundle axial relative exposure shape** is defined as that shape which is uniquely consistent with the uncontrolled axial relative power shape assuming uniform fuel density; and
- The **bundle axial void fraction shape** is defined as a shape which is consistent with the uncontrolled axial relative power shape and gives a prototypical bundle average void fraction.

Figure A-1 provides a summary of these normalized axial shapes for GE14 fuel. The corresponding numbers are listed in Table 8-2.

[[

]]

Figure 8-1. GE14 Axial Shapes for Rod Power Integration

8.4 R-FACTOR DISTRIBUTION

[[

[[ ]]

8.5 R-FACTOR CALCULATION EXAMPLES

Using the procedures defined in the previous sections, R-factors are calculated for different lattice locations in a bundle as a function of fuel assembly exposure, control state and channel bow using Equation 8-1. The following example is for a 10x10 lattice (GE14).

Consider Equation 8-1 for the various cases as shown in Figure 8-2:

Corner Rod:
Applying Equation 8-1 to a corner rod (as in Figure 8-2a),

[[ ]] (8-2)

Side Rod:
Applying Equation 8-1 to a side rod (as in Figure 8-2b),

[[ ]] (8-3)

Interior Rod:
Applying Equation 8-1 to an interior rod (as in Figure 8-2c),

[[ ]] (8-4)

If there is one unheated lattice position (as in Figure 8-2d),

[[ ]] (8-5)

If there are two unheated lattice positions (as in Figure 8-2e),

[[ ]] (8-6)

If there are four unheated lattice positions (as in Figure 8-2f),

[[ ]] (8-7)

A summary of the R-factor calculational method for each GE14 lattice position (as identified in Figure 8-3) is given in Table 8-1.

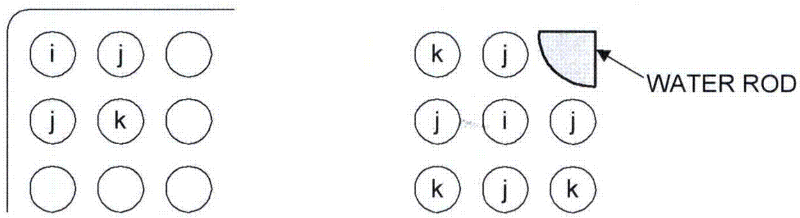

Figure 8-2a ....

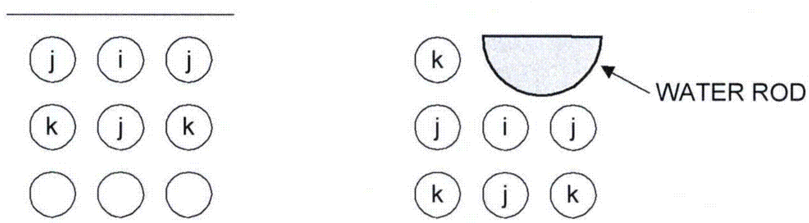

Figure 8-2b ....

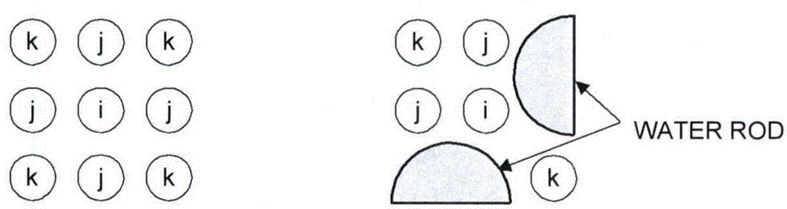

Figure 8-2c ....

Figure 8-2. Identification of Rods in Positions Adjacent to Rod i

Table 8-1. R-factor Calculation by Lattice Position

Lattice Position	Apply Figure	Use Equation
1,1	8-2a	8-2
1,2	8-2b	8-3
1,3	8-2b	8-3
1,4	8-2b	8-3
1,5	8-2b	8-3
2,2	8-2c	8-4
2,3	8-2c	8-4
2,4	8-2c	8-4
2,5	8-2c	8-4
3,3	8-2c	8-4
3,4	8-2c	8-4
3,5	8-2d	8-5
3,3A	8-2d	8-5
3,4A	8-2e	8-6
3,5A	8-2e	8-6
4,4	8-2c	8-4
4,5	8-2e	8-6
5,5	8-2f	8-7

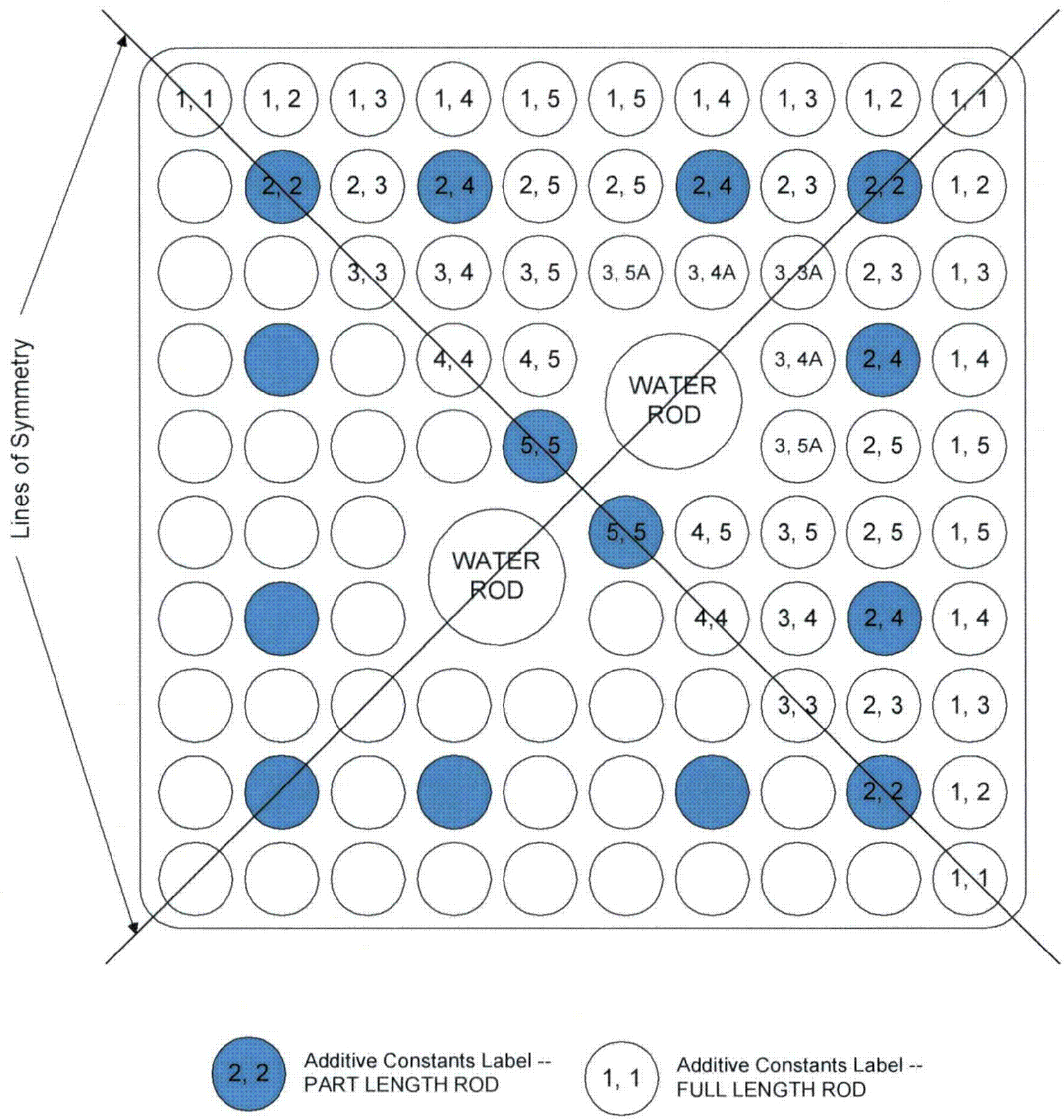

Figure 8-3. GE14 10x10 Lattice

8.6 FUEL ASSEMBLY R-FACTOR

The fuel assembly R-factor is determined in accordance with Equation 8-8 for any specified fuel assembly exposure, control state and channel bow.

$$R = \overline{Max}\left[R_i\right] \qquad \text{taken over all } i \qquad (8\text{-}8)$$

[[

]] of R-factors as illustrated in Figure 8-4.

[[

]]

R_{UC} = R-factor at uncontrolled state.
R_{BP1} = R-factor at first break point control fraction,
R_{BP2} = R-factor at second break point control fraction
R_{FC} = R-factor at fully controlled.
BP1 = Control fraction at the first break point for this 3-segment straight line model.
BP2 = Control fraction at the second break point.

Figure 8-4. R-Factor for the Partially Controlled Assembly

Table 8-2. GE14 Axial Shapes for Rod Power Integration

Axial	Axial power shapes with number of nodes controlled											Void	Relative
Node	0	2	3	4	5	6	8	10	12	15	20	25	Fraction	Exp.

[[

]]

9. NOMENCLATURE

The nomenclature used in this report is provided below. The units shown here are general dimension of the variables. Actually units required for dimensional calculations (V(I) terms in Eq. 5-2) are described in section 5.

Symbol	Definition	Units
A	Bundle flow area	ft^2 (m^2)
A(I)	Fuel type specific GEXL coefficients	Values in Section 5 consistent with specific English units
D_H	Hydraulic diameter	ft (m)
D_Q	Thermal diameter	ft (m)
F	Number of active fuel rods	dimensionless
G	Mass flux	lb/ft^2-sec (kg/m^2-sec)
G_f	Mass flux of the liquid phase alone	lb/ft^2-sec (kg/m^2-sec)
G_g	Mass flux of the gaseous phase alone	lb/ft^2-sec (kg/m^2-sec)
g	Gravitational constant	ft/sec^2 (m/sec^2)
h_f	Saturated liquid enthalpy	Btu/lb (kJ/kg)
h_g	Saturated vapor enthalpy	Btu/lb (kJ/kg)
h_{in}	Inlet liquid enthalpy	Btu/lb (kJ/kg)
j_f	Average liquid velocity = $W_f/\rho_f A = G_f/\rho_f$	ft/sec (m/sec)
j_g	Average vapor velocity = $W_g/\rho_g A = G_g/\rho_g$	ft/sec (m/sec)
j_f^*	Dimensionless liquid velocity	dimensionless
j_g^*	Dimensionless vapor velocity	dimensionless
L_A	Annular flow length	ft (m)
L_B	Boiling length	ft (m)
l_i	Additive constant	dimensionless
n_j	Number of rods in position j	dimensionless
n_k	Number of rods in position k	dimensionless
P	Pressure	psi (MPa)
q	Correction for adjacent low power rods	dimensionless

$Q(z)$	Integrated power input to the coolant up to location (z)	BTU/sec (Watts)
R	Bundle R-factor	dimensionless
R_i	R-factor for an individual rod	dimensionless
R_{FC}	R-factor at fully controlled	dimensionless
r_i	Local peaking factor for rod i	dimensionless
r_j	Local peaking factor for rod j	dimensionless
r_k	Local peaking factor for rod k	dimensionless
T	Total number of lattice positions	dimensionless
$V(I)$	GEXL correlation parameters	Values in Section 5 consistent with specific English units.
W	Bundle coolant flow rate	lb/hr (kg/sec)
W_f	Liquid mass flow	lb/hr (kg/sec)
W_g	Vapor mass flow	lb/hr (kg/sec)
W_i	Weighting factor for rods in position i	dimensionless
W_j	Weighting factor for rods in position j	dimensionless
W_k	Weighting factor for rods in position k	dimensionless
X	Local quality	dimensionless
X_C	Critical quality	dimensionless
X_{TR}	Annular flow transition quality	dimensionless
Z_C	Axial coordinate for the point of critical quality	ft (m)
Z_{TR}	Axial coordinate for the point of transition to annular flow	ft (m)
z	Axial coordinate for elevation in bundle	ft (m)
ρ_f	Liquid density	lb/ft^3 (kg/m^3)
ρ_g	Vapor density	lb/ft^3 (kg/m^3)

10. REFERENCES

1. NEDO-10958A and NEDE-10958P-A, *General Electric BWR Thermal Analysis Basis (GETAB): Data, Correlation and Design Basis*, January 1977.

2. NEDE-32199P, *COBRAG Model Description*, April 1993.

3. NEDE-24011-P-A-14, *General Electric Standard Application for Reactor Fuel (GESTAR II)*, June 2000.

4. NEDC-32505P-A, *R-Factor Calculation Method for GE11, GE12, and GE13 Fuel*, Revision 1, July 1999.

5. MFN-046-98, Letter Thomas. H. Essig to Glen A. Watford, "ACCEPTANCE FOR REFERENCING OF LICENSING TOPICAL REPORT NEDC-32505P, REVISION 1. "R-FACTOR CALCULATION METHOD FOR GE11, GE12 AND GE13 FUEL" (TAC NO. M99070 AND M95081)," January 11, 1999.

APPENDIX A. COBRAG SUBCHANNEL ANALYSIS

A.1 INTRODUCTION

COBRAG (Reference 2) is a steady-state subchannel analysis code for performing analysis on BWR fuel bundles. It can be used to predict bundle critical powers and dryout locations, bundle planar averaged and local void fractions and bundle pressure drops.

A.2 COBRAG MODEL

COBRAG is capable of simulating a broad range of bundle geometries. Bundles with large water rods, part length rods, and full length rods can be modeled with their own specific size, axial power profile, and local peaking. Bundle inlet and outlet conditions, including inlet flow distributions, are simulated as boundary conditions specified by input.

The subchannel two-phase flow is described by a two-fluid, multi-field model. Interactions between the fields are modeled through constitutive correlations for interfacial shear and heat transfer, entrainment and deposition. Inter-subchannel transport phenomena like mixing and void drift are also modeled. Energy transfer from the channel wall is modeled as a boundary condition. Physical models include a full or part length rod model with its own specific axial power profile and peaking factor, and a semi-empirical spacer model.

A.3 COBRAG QUALIFICATION

Extensive comparisons have been made between COBRAG and ATLAS critical power measurements for 8x8, 9x9 Zircaloy and 10x10 Inconel spacer (GE12) and 10x10 Zircaloy spacer (GE14) designs. The critical power results are summarized in Table A-1. The overall ECPR for each design is very close to 1.0, and the variation between designs is quite small. Therefore COBRAG is capable of predicting the change between lattice types (8x8, 9x9 and 10x10), change in axial power shape (GE11 and GE13 inlet, cosine and outlet), the effect of part length rods (GE11 and similar prototype with all full length rods tests) and effect of spacer locations. [[

]] Figures A-1 through A-5 show the COBRAG critical power plotted versus the ATLAS critical power for the three GE11 power shapes and the GE12 cosine axial power shape. Figure A-6 shows the COBRAG predicted GE14 critical power versus the ATLAS critical power test data for the cosine power shape. Figure A-7 shows the COBRAG predicted GE14 critical powers for inlet [[ ]] and outlet [[ ]] peak power shapes versus predicted cosine critical powers.

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Figure A-1. GE11 COBRAG/ATLAS Critical Power Comparison

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Figure A-2. GE11 COBRAG/ATLAS Inlet Peak Critical Power Comparison

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Figure A-3. GE11 COBRAG/ATLAS Cosine Critical Power Comparison

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Figure A-4. GE11 COBRAG/ATLAS Outlet Peak Critical Power Comparison

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Figure A-5. GE12 COBRAG/ATLAS Critical Power Comparison

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Figure A-6. GE14 COBRAG/ATLAS Critical Power Comparison

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Figure A-7. GE14 COBRAG Predicted Critical Power for Inlet and Outlet Peaked Power Shape

Table A-1. Summary of COBRAG/ATLAS Critical Power Comparisons

Condition	Average ECPR	Standard Deviation (%)
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A.4 GEXL14 AXIAL POWER SHAPE EFFECT USING COBRAG

The comparisons between the COBRAG results and GEXL14 results are summarized in Tables A-2, A-3 and A-4. The figure for comparison is the CCPR ratio, defined as:

$$\text{CCPR} = (\text{GEXL14 Critical Power})/(\text{COBRAG Critical Power}) \qquad \text{(A-1)}$$

To determine the CCPR select a representative number of assemblies and use the COBRAG program to calculate inlet and outlet peaked critical power values for a matrix of flow and inlet subcooling values. The COBRAG subchannel code has previously been extensively qualified against GE11/13 cosine, inlet and outlet peaked power shape data. The COBRAG input was first set up to simulate the measured cosine power distribution and measured radial power distribution. The input axial power distribution was then changed to either the inlet or outlet peak axial power distribution. The inlet and outlet peak rod power shapes are identical to those used for GE11 and GE13 ATLAS testing.

Table A-2 shows the CCPR trend versus the two peaking patterns analyzed. [[

]] Table A-3 shows the trend versus flow and subcooling. [[ ]] Table A-4 shows the trend versus subcooling, [[

]] Table A-5 summarizes the GEXL comparisons to ATLAS data and COBRAG for all power shapes. [[
]] In summary, the GEXL14 correlation agrees very well with the COBRAG subchannel analyses and there are no strong trends in the data.

Table A-2. GE14 GEXL14/COBRAG Critical Power Comparison

Assembly	Inlet Peak		Outlet Peak		Combined Inlet and Outlet Peak	
	CCPR	σ (%)	CCPR	σ (%)	CCPR	σ (%)
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Table A-3. GE14 GEXL14/COBRAG Critical Power Mass Flux Trend

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Table A-4. GE14 GEXL14/COBRAG Critical Power Subcooling Trend

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Table A-5. GEXL14 ECPR and COBRAG CCPR Comparison for All Power Shapes

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