ENCLOSURE 2

FLN-2008-009

Correction Pages for NEDO-32851-A, Revision 4

GEXL14 Correlation for GE14 Fuel

Non-Proprietary Information

IMPORTANT NOTICE

This is a non-proprietary version of Enclosure 1 to FLN-2008-009, which has the proprietary information removed. Portions of the document that have been removed are indicated by white space with an open and closed bracket as shown here [[ ]].

Revision Status

Revision	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
5	Revision 5 corrects several of the published additive constant values and comparative statistics, which were not documented correctly in the Revision 4 report. The conclusions regarding the correlation statistics are unaffected.	
	Section 3	Editorial correction. Figures 3-3 and 3-4 at bottom of page 3-2 should be 3-2 and 3-3.
	Section 4	Section 4.3 Reference to GETAB should be Reference 1. Table 4-4 and 4-5 were updated consistent with the minimum annular length. Table 4-6: Correct Corner Rod and Outer Rod values for GE14 and GE12 with Zircaloy spacers. Table 4-7 and 4-8 were updated to be consistent with the results from Table 4-4 and 4-5. Corrected additive constant in Section 4.8. Table 4-9 was updated and a short discussion was added to explain the significance of the change in statistics.
	Section 7	Statistics in Section 7 and shown on Figure 7-1 and 7-2 were made consistent with values in Section 4.
	Appendix A	Table A-5 was updated consistent with Table 4-4.

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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 Figure 3-1. 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 3-2 and 3-3. [[

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.
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  ]] 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. [[

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. [[

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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				]]

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						]]

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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
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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 (%)			]]

The established statistics used in GE14 Safety Limit MCPR analyses are a Mean ECPR of [[ ]] and Standard Deviation of [[ ]], as given in NEDC-32851P, Revision 2. The GETAB Method values in Table 4-9 above would yield a change in Safety Limit of approximately 0.0005, which is insignificant. Therefore, the current Mean ECPR of [[ ]] and Standard Deviation of [[ ]] are retained.

4.7 POWER SHAPE SENSITIVITY COMPARISON

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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

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4.9 PRESSURE RANGE

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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. [[

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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:

$$ECPR \equiv \frac{\text{PredictedCriticalPower}}{\text{MeasuredCriticalPower}} \qquad (7\text{-}1)$$

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 [[

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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.

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

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

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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