ENCLOSURE 5

FLN-2007-011

GEXL17 Correlation for GNF2 Fuel, NEDC-33292P, March 2007

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GNF

Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

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GEXL17 CORRELATION FOR GNF2 FUEL

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Revisions

Revision 1 of NEDO-33292, dated March 2007, is the non-proprietary version of NEDC-33292P, Revision 1. Because Revision 0, dated November 2006, was an internal document, there was no non-proprietary version of Revision 0.

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 and at the Stern Laboratories test facility in Hamilton, Ontario. The database supporting the basic GEXL correlation includes over 22,000 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 and Stern facilities 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 GNF2 GEXL17 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 GEXL17 correlation is used to determine the expected thermal margin for the operating cycle. In the safety analysis process, the GEXL17 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 and in determining the depth of penetration of the dryout location. 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.

1.0   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 is described in Reference 2.

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).

The GEXL correlation was modified in 1986 to include two additional terms as a function of the annular flow length (Reference 4). This improved the correlation prediction of axial power shape trends.

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 GEXL17 correlation was collected in the Stern Labs test facility and is described in Sections 3.0 and 4.0.

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 either the ATLAS test facility or the Stern Labs test facility for developing the correlation coefficients for new fuel designs. The exact form of the correlation and the coefficients for GNF2 fuel are provided in Section 5.0.

Transient tests simulating turbine trip and all pump trip events are documented in Section 6.0. 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. Its capability for predicting GNF2 fuel is provided in Section 7.0. An overview of the process to calculate R-factors, a key parameter in the correlation, is given in Section 8.0. The nomenclature and references used in this report are provided in Sections 9.0 and 10.0, respectively.

2.0 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.

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 original form of the GEXL01 correlation (Reference 1) was first modified (Reference 4) in the GEXL-Plus correlation and subsequently in later versions to incorporate the annular flow length parameter with the addition of two new terms. GEXL17 is based on extensive full-scale critical power tests of GNF2 10x10 fuel assembly designs. In addition, the GEXL17 correlation builds on the experience gained from the previous GE11 and GE13 9x9 fuel, and GE12 and GE14 10x10 fuel designs. The GEXL17 correlation maintains the basic form of the GEXL-Plus.

3.0　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.

As described above, the original GEXL01 correlation was developed based on a wide variety of test geometries. Included were data for 7x7 and 8x8 fuel designs using a mixture of full and reduced length 16 rod, 49 rod, and 64 rod test assemblies with different bundle spacer designs. 7x7 data was collected for multiple axial power shapes including uniform, cosine, inlet, outlet, and double humped. 8x8 data was collected for cosine axial power shape only. A description of this database is provided in Reference 1. The axial power shape effect for 8x8 fuel was accounted for with a statistical adder, the variance of the means for all 7x7 power shapes, to the 8x8 cosine data uncertainty as approved in Reference 1.

The GEXL-Plus improved critical quality correlation includes the addition of annular flow length terms to the original GEXL01 correlation. It was developed to better predict the axial power shape effect for 8x8 and later fuel designs. The 8x8 database was expanded for the development and included additional cosine and inlet axial power shape data. GEXL-Plus was approved in GESTAR-II, Amendment 15 (Reference 2) based on cosine and inlet peaked power shape data. The GEXL-Plus correlation has been used for all subsequent 8x8 fuel designs, this included 8x8 fuel designs with ferrule spacers and a large central water rod (GE9 and GE10).

[[

]]

ATLAS testing was conducted for GE12 and GE14 10x10 fuel using [[

]] 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. [[

]] This used the process previously approved in Reference 1.

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 Alloy X-750 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. GEXL14 was developed based on separate testing databases for 10x10 GE14 fuel, which has Zircaloy ferrule spacers [[

]]

GNF2 fuel, an improved 10x10 bundle design, has two part length rod lengths and uses a new Ni-based alloy grid spacer design with flow wings. In Section 5.0, the final GEXL17 correlation for licensing GNF2 fuel is given, including additive constants. The database for GNF2 fuel is summarized in Table 3-1, Table 3-2 and Figure 3-1, which show the number of data points collected for various mass flux, pressure, and inlet subcooling combinations, and the number of points collected when dryout occurred for each unique rod location.

The critical power testing for the GEXL17 development was performed on full-scale GNF2 test assemblies [[

]] All testing was completed in the Stern Laboratories test facility in Hamilton, Ontario. The GNF2 test data used in the GEXL17 correlation development was generated using assemblies with the same number of heated rods and assembly geometry as the GNF2 bundle design. From the thermal hydraulic perspective, the only difference between all test assemblies and an actual GNF2 fuel assembly was the use of electrically heated rods instead of fuel rods. All simulations included heated part length rods. The spacers for all test assemblies were manufactured using the same materials and to the same specifications as reactor quality spacers.

The GNF2 test assembly characteristics are provided in Table 3-3 and Figure 3-2. The tests were performed [[   ]] The axial power profile, for both the full length and part length rods, used in the Stern tests are shown Figure 3-3 and Figure 3-4. In the Stern tests, springs were attached to two adjacent sides of each spacer band so that the most limiting corner of the bundle (highest R-factor rods) had the minimum rod to channel gap. Based on previous test experience this configuration provides the most conservative critical power, and the results are very reproducible.

Table 3-1. GEXL17 Database Collection – Mass Flux vs. Pressure

	Pressure (psia)									
Mass Flux (Mlb$_m$/hr-ft^2)	[[									
										]]

Table 3-2. GEXL17 Database Collection – Inlet Subcooling vs. Mass Flux

	Mass Flux (Mlb$_m$/hr-ft^2)												
Inlet Subcooling (BTU/lb$_m$)	[[												
													]]

[[

]]

Figure 3-1. GEXL17 Database Collection by Unique Rod Location

Table 3-3. STERN GNF2 Test Assembly Characteristics

[[	
	]]
Lattice	10x10
[[	
	]]
Number of Full Length Heated Rods	78
[[	]]
Number of Heated Part Length Rods	6 Short, 8 Long
[[	
	]]
Number of Water Rods	2
[[	]]
Number of Spacers on the Heated Length	8
Spacer Type	Ni-based alloy Grid with Flow Wings
[[	
	]]
[[	
	]]

[[

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Figure 3-2. GNF2 Test Assembly Rod Numbering System

[[

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

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Figure 3-4. Typical Bundle Axial Heat Shape - Stern Critical Power Tests

4.0   TEST MATRIX AND CORRELATION PROCEDURES

4.1   Introduction

The GNF2 10x10 fuel design is an evolutionary product based on the experience gained in the GE9/10 8x8, the GE11/13 9x9 and GE12/14 10x10 fuel designs. In each case, critical power performance estimates and Stern test matrix procedures have been derived from the results obtained with previous tests. In the GE9/10 fuel designs, [[

]]

4.2   The GNF2 10x10 STERN Test Matrix

The GNF2 10x10 Stern test matrix is outlined in Table 4-1. This test matrix, consisting of [[   ]] test points, follows the same test philosophy as previous correlations. More peaking patterns were tested than with 9x9 designs because the 10x10 lattice contains more unique lattice positions – [[   ]]. The GNF2 test matrix [[

]]

Table 4-1. GNF2 Stern Test Matrix Critical Power (Steady-state)

[[	
	]]

Table 4-1. GNF2 Stern Test Matrix Critical Power (Steady-state), continued

[[	
	]]

4.3   Correlation Procedure for GEXL17

The procedure used for the GEXL17 correlation can be summarized as follows:

[[

]] 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 correlations. [[

]] Therefore the first requirement is satisfied. [[

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

These steps were taken to optimize GEXL17 for the GNF2 product line, minimize the prediction uncertainty and ensure that the axial power shape effects were accurately accounted for.

5.0   CRITICAL POWER CORRELATION

5.1   Form of the GEXL Correlation

As discussed in Section 2.0, the critical quality versus boiling length plane was chosen by GE as the coordinate system for correlating the boiling transition data described in Section 3.0. 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 5-1.

Table 5-1. GEXL17 Correlation Coefficients

I	V(I)	A(I)
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-hr.

L_B Boiling length, in.

L_A Annular length, in.

P Pressure, psia.

R Bundle R-factor.

5.2   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.

5.2.1 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.

5.2.2 Thermal Diameter

The thermal diameter, D_Q, is a characteristic diameter defined in the fully rodded, large water rod diameter 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 development of the GEXL17 correlation for GNF2 fuel is given at the bottom of Table 3-3. This parameter is taken as constant for a fuel assembly as an input to the correlation.

5.2.3 Mass Flux

The mass flux, G, is defined as the bundle active coolant flow per unit flow area in the fully rodded, large water rod diameter region. The flow area used in the development of the GEXL17 correlation for GNF2 fuel is given at the bottom of Table 3-3. The mass flux is taken as constant for the fuel assembly as an input parameter to the correlation.

[[

]] Figure 5-1 graphically describes the exception and how it is to be applied.

[[

]]

Figure 5-1. Critical Power Calculation in High R-factor and High Mass Flux Region

5.2.4 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.

5.2.5 R-Factor

The R-factor is a parameter that 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. An overview of the R-factor calculation method is provided in Section 8.0. In addition, there is an additive constant applied to each fuel rod location [[

]] For GNF2, the additive constants used in the design process are provided in Table 5-2. [[

]] (see Figure 5-2).

Table 5-2. GEXL17 Additive Constants for GNF2 with Ni-based alloy Grid Spacer

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

[[

]]

Figure 5-2. Additive Constant Symmetrical Application

In order to compare the relative performance of the GNF2 design with the GE14 design, one can compare both the additive constants and the GEXL correlation prediction. Given the same flow conditions and R-factor, GEXL14 and GEXL17 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 5-3 presents such a comparison, giving the average additive constants for the outer rod row, second row, etc. The results in Table 5-3 also show the magnitude of the additive constants difference, which can be translated into a performance enhancement of GNF2 over GE14. [[

]]

Table 5-3. Comparison of GNF2 and GE14 Additive Constants

[[				
				]]

5.2.6 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 5-4 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 [[

]]   (5-4)

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

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

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

and where D_H is the hydraulic diameter of the fully rodded region (the value used in the correlation development is shown at the bottom of Table 3-3),

$$G_g = XG \qquad (5-7)$$

$$G_f = (1 - X) \, G \qquad (5-8)$$

Combining these expressions gives the annular flow transition quality

[[   ]]   (5-9)

Thus the annular flow length is given by

            [[   ]]   (5-10)

where

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

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, boiling length, and annular flow 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 5-3 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:

$$X(z) = \left[Q(z)/W - (h_f - h_{in}) \right] / (h_g - h_f)$$ (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 5-3. 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 5.4. GEXL is used under transient conditions in the similar manner as it is used under steady-state conditions described above.
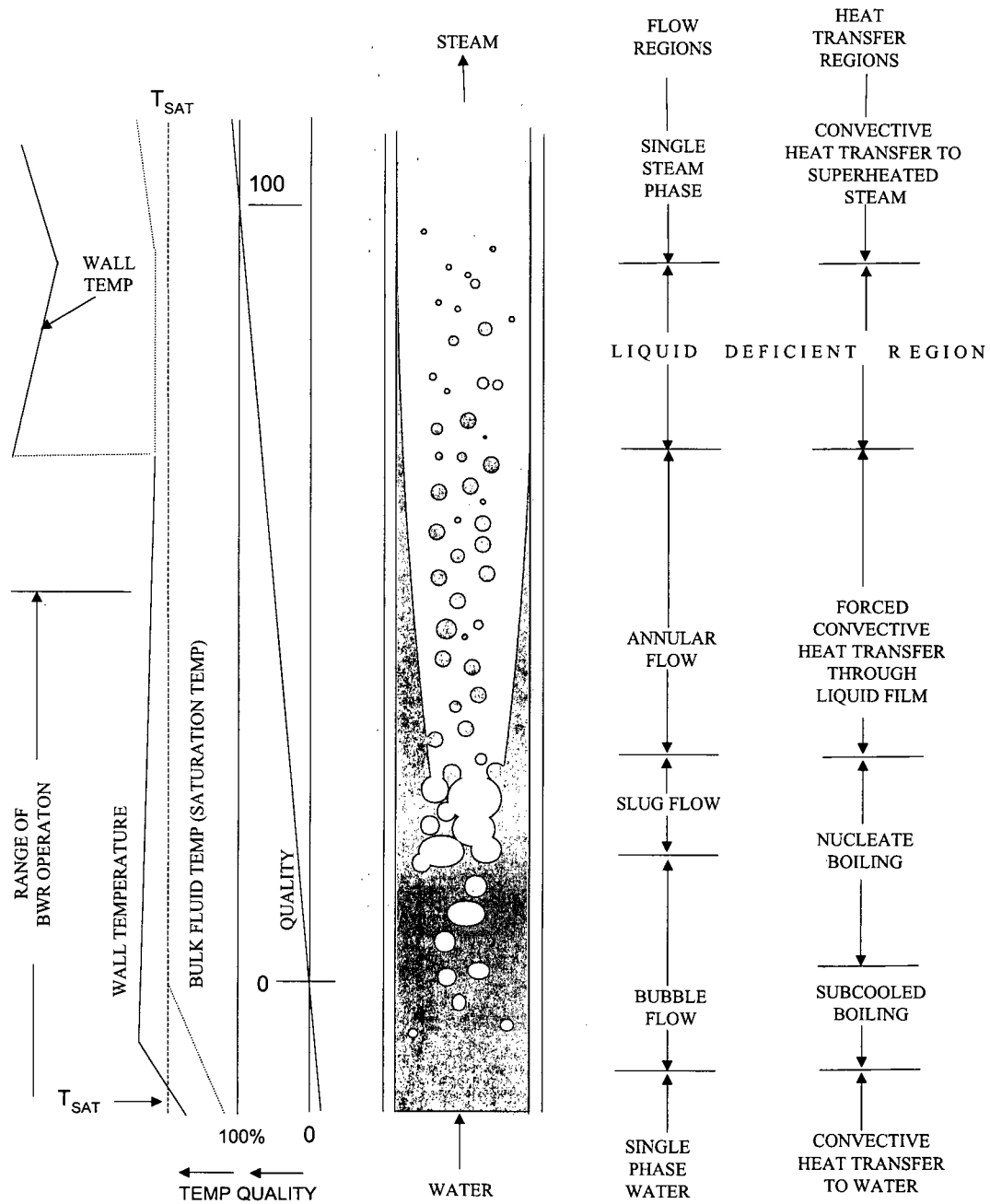
Figure 5-4. Regimes of Two-Phase Flow

5.4　GEXL17 Application Range

The GEXL17 correlation for GNF2 fuel is valid over the range stated in Table 5-4.

Table 5-4. GEXL17 Correlation Application Range

[[	
	]]

[[

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5.5　GEXL17 Correlation Trends and Database Statistics

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. [[

]] Figure 5-5 thru Figure 5-8 show the ECPR trends as well as the range of data collection for pressure, mass flux, R-factor, and inlet subcooling parameters.

A statistical analysis has been performed for the GNF2 database used to develop the GEXL17 correlation, consisting of [[ ]] data points for [[ ]] different local peaking patterns. A summary of the correlation statistics is given in Table 5-5. Note that although there were [[ ]] points collected and used in the correlation development, only [[ ]] were used in the correlation statistics. The correlation database is comprised of two separate sets of data: (1) the development database used for determination of the correlation coefficients and (2) the verification database that is held out from the development of the correlation coefficients in order to verify the validity of the correlation without commingled data. [[

]] The statistical summary is further evaluated in Table 5-5 separately [[

]]

Table 5-5. GEXL17 Statistical Summary

[[					
					]]

[[

]]

Figure 5-5. GNF2 Test Data vs. GEXL17 Calculated Critical Power

[[

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Figure 5-6. GEXL17 Mass Flux Trends

[[

]]

Figure 5-7. GEXL17 Pressure Trends

[[

]]

Figure 5-8. GEXL17 Inlet Sub-cooling Trends

5.6 Power Shape Sensitivity Comparison

As previously discussed in Section 3.0, the introduction of part length rods did not introduce any new sensitivities in the correlation development. Figure 5-9 [[

]] for GNF2 (GEXL17), GE14 (GEXL14), GE12 (GEXL10), GE11 (GEXL07) and GE13 (GEXL09). The latter two are correlations for 9x9 bundles for which ATLAS tests [[

]]

[[

]]

Figure 5-9. Power Shape Sensitivity Comparison for 9x9 and 10x10 Fuel Designs

5.7   GEXL17 Correlation Statistics

The GEXL17 axial power shape effects were evaluated using the GNF2 [[

]] The

comparisons show that GEXL17 power shape effects are well predicted compared to Stern data and consistent with the trend observed for previous fuel designs. Based on these evaluations, a conservative correlation uncertainty was determined using the previously approved methods form GETAB (Reference 1).

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

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

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

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

where the summation is over the data in set j.

The following relation exists:

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

Equations 4-5 and 4-6 are the basis for the GETAB process (Reference 1) that was used to develop the correlation uncertainty for the 8x8 GEXL01 correlation where only cosine data existed. The first term in the equation 4-6 is the average of the standard deviation for the data sets. The second term is the variance of the means for the data sets and represents the trend error in predicting the axial power shape effects. This term is very similar for the different fuel types. The standard deviation is very similar for the different data sets and therefore the standard deviation for cosine data is similar to the average of the standard deviation for all the sets. The

original GETAB process (Reference 1) follows this logic and determined the 8x8 correlation uncertainty using the following:

$$\sigma^2_{8X8} = \sigma^2_{8x8, cosine\ data} + (Variance\ of\ means)_{7x7\ all\ power\ shapes}$$

[[

]]

Table 5-6. 9x9 and 10x10 Axial Power Shape Sensitivities

Power Shape	9x9 Fuel				10x10 Fuel	
	GE11 (GEXL07)		GE13 (GEXL09)		GNF2 (GEXL17)	
	ECPR	σ (%)	ECPR	σ (%)	ECPR[†]	σ (%)[†]
[[						
						]]

[[

                                                                    ]]

Several observations can be made from this table:

[[

                                                        ]]

Following the GETAB process the total correlation uncertainty can be determined as:

[[

]]

Table 5-7. Historical Uncertainty Adders

Fuel Type	σ_1	σ_2
[[		
		]]

[[

]]

Table 5-8. GEXL17 Correlation Bias and Uncertainty

[[		
		]]

5.8   GEXL Correlation Interfaces

As described in Section 1.0, GEXL interfaces with the core design and transient analysis process in several places: the core nuclear design and management process through the three-dimensional BWR simulator; the determination of the MCPR safety limit; the determination of the transient change in CPR during abnormal operational occurrences (AOO) and for the determination of the corresponding operating limit MCPR; and for the calculation of boiling transition during accidents and severe transients. The following describes the use of the GEXL correlation, in core nuclear design and management, in the determination of the MCPR safety limit, and in the transient analysis process.

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 bundle power, R-factor, inlet flow and subcooling, pressure and power shape. [[

]]

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.

In the analysis of AOO transients, 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 ΔCPR is then used to set the operating limit MCPR such that a very high percentage of the fuel rods in the core would be expected to avoid boiling transition.

For accidents and severe transients such as loss of coolant accidents (LOCA) and anticipated transients without scram (ATWS), the GEXL correlation is used to determine the condition when boiling transition and subsequent fuel heatup will occur.

5.9   Conclusion

The GEXL17 correlation has been validated against Stern data for [[

]]

6.0 TRANSIENT QUALIFICATION

Changes in critical power during an operational transient are calculated with a two-phase transient thermal hydraulic model. The 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 GEXL17 correlation is used together with the transient thermal hydraulic conditions computed by the program to compute the change in CPR during a given transient. The qualification of GEXL17 is accomplished by comparing the change in critical power ratio with experimental results obtained from the Stern thermal hydraulic test facility.

In addition to measuring steady state critical power, the Stern 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 functions 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 GEXL17 correlation, three transient tests were performed in the manner described above. The experimental conditions are summarized in Table 6-1.

Table 6-1. Summary of GEXL17 Transient Tests

[[

]]

A comparison of calculated versus measured results is summarized in Figure 6-2 along with a comparison of transient data for some previous fuel product lines. These results show that the   GEXL17   correlation   [[

]] The deviation is similar to that of previous correlations. This uncertainty is consistent with the uncertainty in the GEXL17 correlation.

[[

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Figure 6-1. Transient Test Response for a Turbine Trip without Pump Trip Transient

[[

]]

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

7.0 GNF2 GEXL17 CRITICAL POWER 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 legacy 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 GEXL17 correlation was developed from data obtained in full-scale critical power simulations of GNF2 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 GNF2 lattice configuration also were of particular importance in establishing a GNF2 GEXL correlation. This section provides the results of analyses performed to demonstrate the application of the final GNF2 GEXL17 correlation to predict the GNF2 test data.

A statistical analysis was performed for the GNF2 database consisting of [[   ]] data points for [[   ]] different rod to rod peaking patterns obtained from the Stern test assembly. The data and analyses cover the range for which the GNF2 GEXL17 correlation is considered valid, as identified in Section 5.4. To facilitate the statistical evaluation of the predictive capability of the GNF2 GEXL17 correlation, the concept of an experimental critical power ratio (ECPR) is used. The ECPR is determined from the following relationship:

$$ECPR \equiv \frac{\text{Predicted Critical Power}}{\text{Measured Critical Power}} \qquad (7\text{-}1)$$

Figure 7-1 shows the frequency distribution of all ECPRs for GEXL17 versus test data results for GNF2. The frequency distribution is statistically confirmed as a normal distribution. The

overall statistics for the GEXL17 correlation gives a mean ECPR of [[   ]] and a standard deviation of [[   ]]. The adopted correlation uncertainty for the GEXL17 correlation is [[   ]].

In summary, critical power data recorded under simulated reactor operating conditions with GNF2 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. [[   ]]

[[

                                                                                    ]]

Figure 7-1. Frequency versus ECPR Histogram for GNF2 Stern Data

8.0   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.

The GEXL17 R-factor calculation process is consistent with the methodology submitted to the NRC and accepted as part of the GE reload licensing application (Reference 3). The validity of this methodology for GNF2 fuel is confirmed by virtue of the adequacy of the GEXL17 correlation statistics and trend characteristics that are based on Stern Labs test data.

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 identical to the uncontrolled axial relative power shape; and

- The **bundle axial void fraction shape** is consistent with the uncontrolled axial relative power shape and gives a prototypical bundle average void fraction.

Figure 8-1 provides a summary of these normalized axial shapes for GNF2 fuel. The corresponding numbers are listed in Table 8-1.

8.4   R-factor Distribution

[[

]]

The R-factor for the ith rod is calculated from the equation:

[[   ]]   (8-1)

where:

[[

]]

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 examples demonstrate the R-factor calculation for the various cases 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),

$$[[\qquad\qquad]] \qquad (8\text{-}3)$$

Interior Rod:

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

$$[[\qquad\qquad]] \qquad (8\text{-}4)$$

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

$$[[\qquad\qquad]] \qquad (8\text{-}5)$$

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

$$[[\qquad\qquad]] \qquad (8\text{-}6)$$

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

$$[[\qquad\qquad]] \qquad (8\text{-}7)$$

A summary of the R-factor calculational method for each GNF2 lattice position (as identified in Figure 8-2) is given in Table 8-2.

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.

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

[[

]]
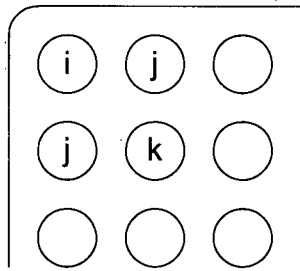
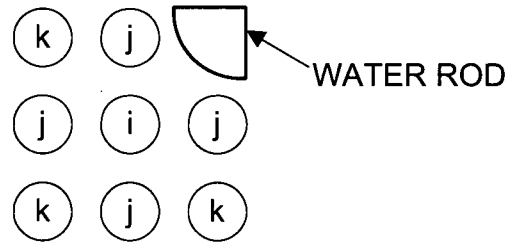**Figure 8-1. GNF2 Axial Shapes for Rod Power Integration**
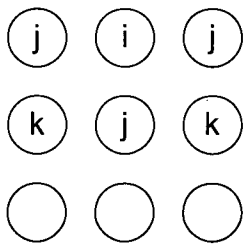
Figure 8-2a

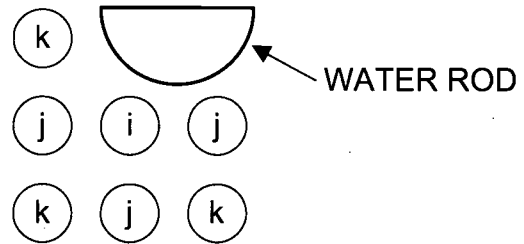**Figure 8-2d**

Figure 8-2b
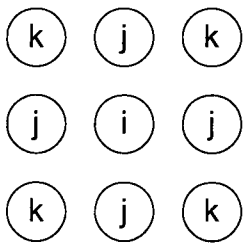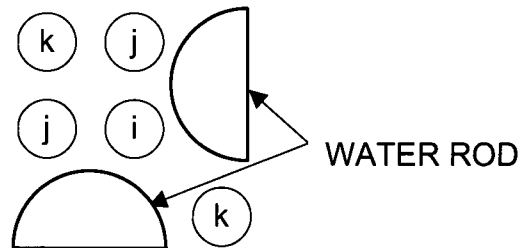

Figure 8-2e

Figure 8-2c

Figure 8-2f

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

Table 8-1. GNF2 Axial Shapes for Rod Power Integration

[[

]]

Table 8-2. 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

9.0 NOMENCLATURE

The nomenclature used in this report is provided below. The units shown here are general dimension of the variables. Actual units required for dimensional calculations ((V(I)) terms in Eq. 5-2) are described in Section 5.0.

Symbol	Definition	Units
A	Bundle flow area	ft^2 (m^2)
A(I)	Fuel type specific GEXL coefficients	Values in Section 5.0 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

Symbol	Definition	Units
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 5.0 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)

10.0 REFERENCES

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

2.   NEDE-24011-P-A-15, *General Electric Standard Application for Reactor Fuel (GESTAR II)*, September 2005.

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

4.   Amendment 15 to GESTAR II (Letter, J. S. Charnley (GE) to C. 0. Thomas (NRC), *Amendment 15 to General Electric Licensing Topical Report NEDE–24011–P–A*, January 25, 1986.