ENCLOSURE 2

M170253

GEXL21 Correlation for GNF3 Fuel, NEDC-33880P Revision 1, November 2017

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Global Nuclear Fuel

NEDO-33880
Revision 1
November 2017

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GEXL21 Correlation for GNF3 Fuel

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Revisions

Revision Number	Page(s)	Description of Change(s)
0	--	Initial issue.
1	8-2	Correction of a typographical error in Equation 8-1.

Acronyms and Abbreviations

Term	Definition
2D	Two-Dimensional
AOO	Anticipated Operational Occurrence
APS	Axial Power Shape(s)
APT	All Pump Trip
ATWS	Anticipated Transients Without Scram
[[	]]
BWR	Boiling Water Reactor
CPR	Critical Power Ratio
ΔCPR	Delta Critical Power Ratio
ECPR	Experimental Critical Power Ratio
FFT	Fast Flow Transient
GE	General Electric Company
GEXL	General Electric Critical Quality - Boiling Length
GEXL01	Original GEXL
GNF / GNF-A	Global Nuclear Fuel – Americas, LLC
ICPR	Initial Critical Power Ratio
LOCA	Loss-of-Coolant Accident
MCPR	Minimum Critical Power Ratio
NRC	Nuclear Regulatory Commission
OLMCPR	MCPR Operating Limit
PLR	Part Length Rod
SLMCPR	MCPR Safety Limit
TTNRPT	Turbine Trip Event Without Recirculation Pump Trip
TTRPT	Turbine Trip Event With Recirculation Pump Trip

Abstract

The General Electric Company (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 GE critical quality - boiling length (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. The data 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 28,000 full-scale boiling transition data points and encompasses all 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 GNF3 GEXL21 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 GEXL21 correlation is used to determine the expected thermal margin for the operating cycle. In the safety analysis process, the GEXL21 correlation is used in the determination of the change in critical power ratio (CPR) during postulated transients and in the determination of an acceptable MCPR safety limit (SLMCPR) 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.

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1.0 Introduction and Summary

The GE critical quality - boiling length (GEXL) correlation was developed to accurately predict the onset of boiling transition in 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 MCPR operating limit (OLMCPR), 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 1.

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 2).

The GEXL correlation was modified in 1986 to include two additional terms as a function of the annular flow length (Reference 3). This improved the correlation prediction of axial power shape (APS) 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 28,000 data points. Of these, over 16,000 points and over 6,000 points have been obtained using full-scale test assemblies in the ATLAS and Stern facilities, respectively. The database supporting the development of the GEXL21 correlation was collected in the Stern Laboratories 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 APS 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 either the ATLAS test facility or the Stern Laboratories test facility for developing the correlation coefficients for new fuel designs. The exact form of the correlation and the coefficients for GNF3 fuel are provided in Section 5.0.

Transient tests simulating turbine trip, fast flow transient (FFT), and all pump trip (APT) 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 GNF3 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 (AOOs). 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 2) was first modified (Reference 3) in the GEXL-Plus correlation and subsequently in later versions to incorporate the annular flow length parameter with the addition of two new terms. GEXL21 is based on extensive full-scale critical power tests of GNF3 10x10 fuel assembly designs. In addition, the GEXL21 correlation builds on the experience gained from the previous GE11 and GE13 9x9 fuel, and GE12, GE14, and GNF2 10x10 fuel designs. The GEXL21 correlation maintains the basic form of the GEXL-Plus correlation.

3.0 Critical Power Database

The current GEXL correlation 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 had 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. The 7x7 data was collected for multiple APS including uniform, cosine, inlet, outlet, and double humped. The 8x8 data was collected for the cosine APS only. A description of this database is provided in Reference 2. The APS 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 2.

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 APS effect for 8x8 and later fuel designs. The 8x8 database was expanded for the development and included additional cosine and inlet APS data. GEXL-Plus was approved in GESTAR II, Amendment 15 (Reference 1) based on cosine and inlet peaked power shape data. The GEXL-Plus correlation has been used for all subsequent 8x8 fuel designs, including 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 GEXL correlations for the 10x10 designs were developed from their respective databases. [[

]] using the process previously approved in Reference 2.

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 PLRs, 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 [[
]] GEXL17 was developed based on the full-scale testing database from Stern Laboratories for 10x10 GNF2 fuel, which introduced two PLR lengths and a Ni-based alloy grid spacer design with flow wings.

GNF3 fuel, an improved 10x10 bundle design, shares many hydraulic characteristics of GNF2 fuel. The GNF3 fuel has two PLR lengths and the GNF3 spacer is a similar design as the GNF2 spacer. The GNF3 spacer is a grid type spacer with flow wings, and the spacer structural material is a Ni-based alloy. The GNF3 spacer includes new design features relative to the GNF2 spacer to improve the mechanical and thermal hydraulic performance. [[

]] In Section 5.0, the final GEXL21 correlation for licensing GNF3 fuel is given, including additive constants. The database for GNF3 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 for each unique rod location.

The critical power testing for GEXL21 development was performed on full-scale GNF3 test assemblies [[

]] All testing was completed in the Stern Laboratories test facility in Hamilton, Ontario. The GNF3 test data used in the GEXL21 correlation development was generated using assemblies with the same number of heated rods and assembly geometry as the GNF3 bundle design, [[

]] the only difference between all test assemblies and an actual GNF3 fuel assembly was the use of electrically heated rods instead of fuel rods from the thermal hydraulic perspective. All simulations included heated PLRs. The spacers for all test assemblies were manufactured using the same materials and to the same specifications as reactor quality spacers. [[

]]

The GNF3 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 rods and PLRs, used in the Stern tests are shown in 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 GEXL21 Database Collection – Pressure versus Mass Flux

		Mass Flux (Mlb$_{m}$/hr-ft^{2})										
[[												
Pressure (psia)												
												]]

Table 3-2 GEXL21 Database Collection – Inlet Subcooling versus Mass Flux

		Mass Flux (Mlb$_{m}$/hr-ft^{2})										
[[												
Inlet Subcooling (BTU/lbm)												
												]]

[[

]]

Figure 3-1 GEXL21 Database Collection by Unique Rod Location

Table 3-3 Stern GNF3 Test Assembly Characteristics

[[	
	]]
Lattice [[Number of Full Length Heated Rods [[Number of Heated Part Length Rods [[Number of Spacers on the Heated Length Spacer Type	10x10]] 80]] 8 Short, 8 Long]] 8 Ni-based alloy Grid with Flow Wings
[[	]]
[[	]]

[[

]]

Figure 3-2 GNF3 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 GNF3 10x10 fuel design is an evolutionary product based on the experience gained in the GE9/10 8x8, GE11/13 9x9, and GE12/14 and GNF2 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 GNF3 10x10 Stern Test Matrix

The GNF3 10x10 Stern test matrix is outlined in Table 4-1. This test matrix follows similar test philosophy as previous correlations but adds more test types and more peaking patterns. Added test types in the GNF3 test matrix are: [[

]]

Table 4-1 GNF3 Stern Test Matrix Critical Power (Steady-State)

[[	
	]]

Table 4-1 GNF3 Stern Test Matrix Critical Power (Steady-State), continued

[[	
	]]

Table 4-1 GNF3 Stern Test Matrix Critical Power (Steady-State), continued

[[	]]

4.3 Correlation Procedure for GEXL21

The procedure used for the GEXL21 correlation can be summarized as follows:

a) [[

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These steps were taken to optimize GEXL21 for the GNF3 product line, minimize the prediction uncertainty, and ensure an accurate accounting of the APS effects.

5.0 Critical Power Correlation

5.1 Form of the GEXL Correlation

As discussed in Section 2.0, the critical quality - 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 GEXL21 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 APS, 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 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 GEXL21 correlation for GNF3 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 region. The flow area used in the development of the GEXL21 correlation for GNF3 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 GNF3, the additive constants used in the design process are provided in Table 5-2. [[ ]] (see Figure 5-2).

Table 5-2 GEXL21 Additive Constants for GNF3 with Grid Spacer

Fuel Rod Lattice Position[1]	Fuel Rod Additive Constant
[[	

]]

[[

]]

Figure 5-2 Additive Constant Symmetrical Application

In order to compare the relative performance of the GNF3 design with the GNF2 design, one can compare both the additive constants and the GEXL correlation prediction. Given the same flow conditions and R-factor, GEXL17 and GEXL21 predict different critical powers. Therefore, the relative critical power between GNF2 and GNF3 fuels cannot be directly compared by using the R-factor or additive constants difference. Instead, the relative performance at each fuel rod position can be compared by using additive constant difference between each rod and average rods. Table 5-3 presents such a comparison, giving the average additive constant differences for the outer rod row and second row. First, the average additive constant of full length rods is calculated using the number of rods and additive constants at each unique rod position. Second, the additive constant difference is calculated by subtracting the additive constant of each rod position by the average additive constant. Finally, the additive constant difference is averaged for corner rod, outer row, second row, and central rods. [[

]]

Table 5-3 Comparison of GNF3 and GNF2 Relative Rod Performance

[[				
				]]

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 5-3 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 [[

]] (5-3)

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

$$j_g^* = G_g\,(\rho_g)^{-1/2}\,[(gD_H)\,(\rho_f-\rho_g)]^{-1/2} \tag{5-4}$$

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

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),

$$G_g = XG \tag{5-6}$$

$$G_f = (1 - X)\,G \tag{5-7}$$

Combining these expressions gives the annular flow transition quality

[[ ]] (5-8)

Thus, the annular flow length is given by

[[ ]] (5-9)

where

$$Z_{TR} = Z \quad \text{when } X = X_{TR}\,. \tag{5-10}$$

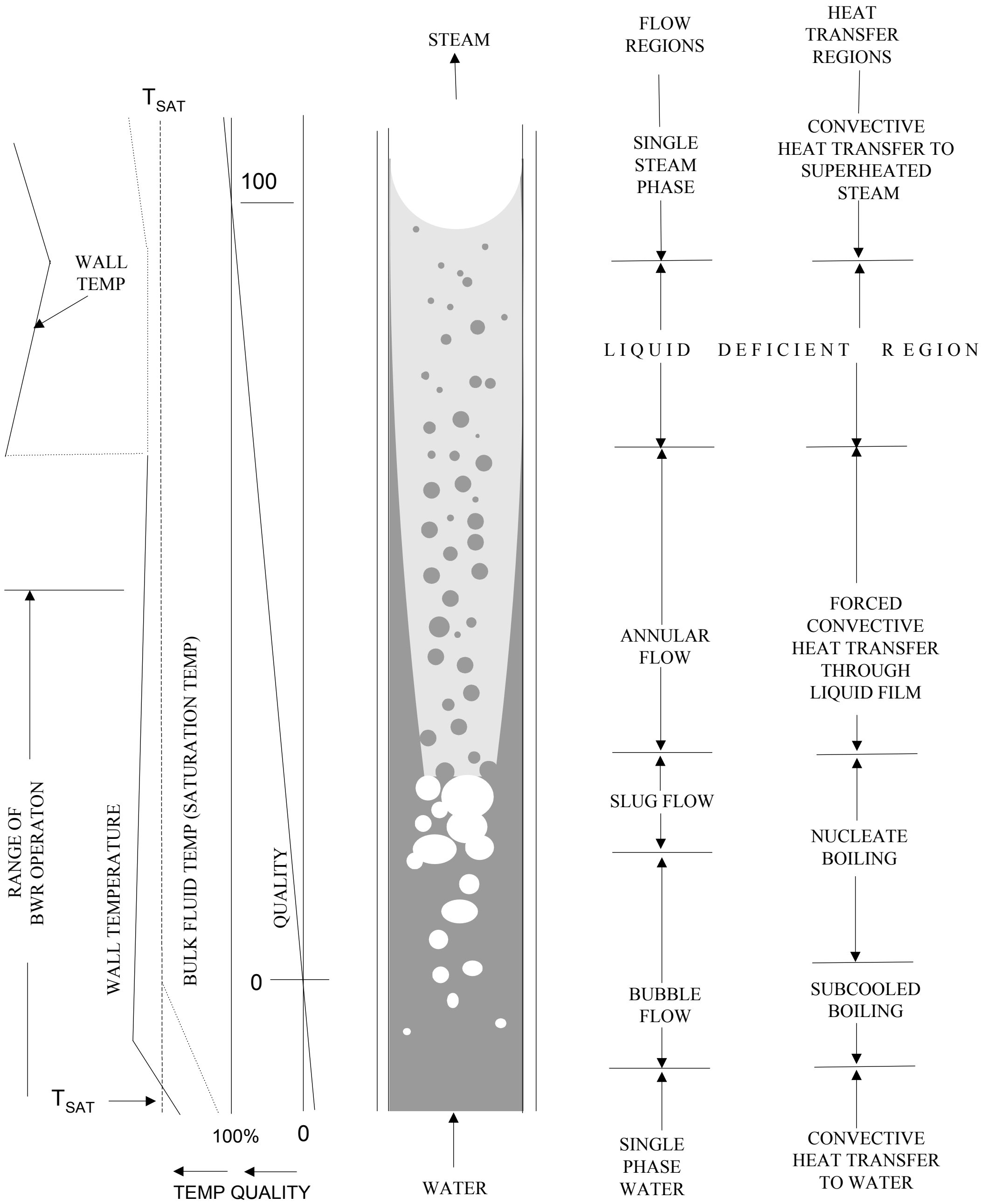

Figure 5-3 Regimes of Two-Phase Flow

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, APS, 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 bundle pressure drop is not considered and the saturation enthalpy at bundle exit pressure is used in the energy and mass balance. 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 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 5-4 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:

$$X(z) = \left[Q(z)/W - (h_f - h_{in})\right] \big/ (h_g - h_f) \tag{5-11}$$

In Equation 5-11, 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.

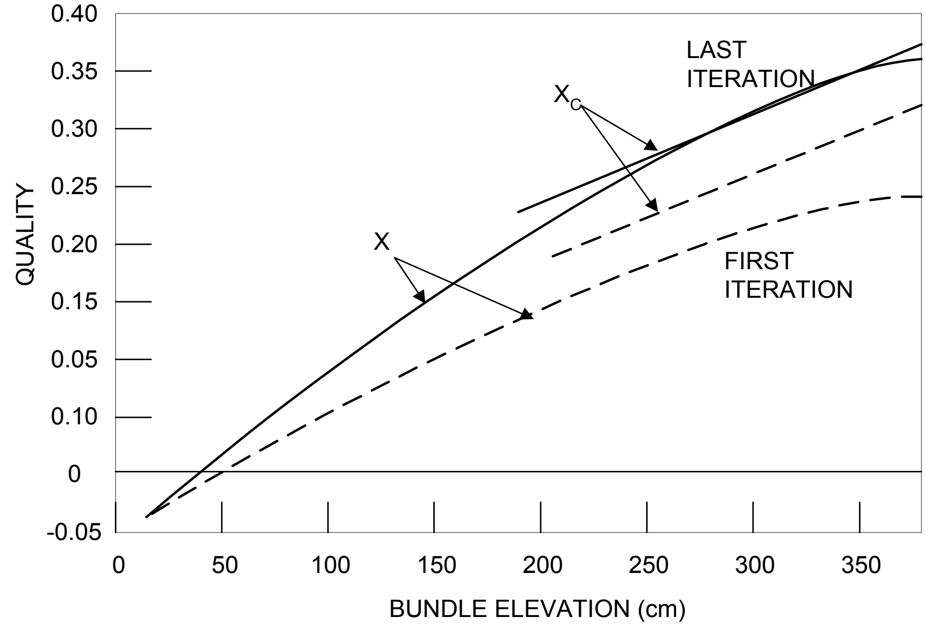

Figure 5-4 GEXL Critical Power Iteration Scheme

The CPR is the ratio of the predicted critical power to the actual power of the particular fuel assembly, with both evaluated at the same pressure, mass flux and inlet subcooling. The 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.

5.4 GEXL21 Application Range

The GEXL21 correlation for GNF3 fuel is valid over the range stated in Table 5-4.

Table 5-4 GEXL21 Correlation Application Range

[[	
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[[

]]

5.5 GEXL21 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 mass flux, pressure, and inlet subcooling parameters.

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 via data not used directly in the correlation development. [[

]]

A statistical analysis has been performed for the GNF3 database used to develop the GEXL21 correlation, consisting of [[ ]] data points for [[ ]] different local peaking patterns. A summary of the correlation statistics is given in Table 5-5. [[

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[[

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Figure 5-5 GNF3 Test Data versus GEXL21 Calculated Critical Power

[[

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Figure 5-6 GEXL21 Mass Flux Trends

[[

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Figure 5-7 GEXL21 Pressure Trends

[[

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Figure 5-8 GEXL21 Inlet Subcooling Trends

Table 5-5 GEXL21 Statistical Summary

[[				
				]]

5.6 Power Shape Sensitivity Comparison

The GEXL21 APS effects were evaluated using the full-scale GNF3 data and through trend comparisons of 9x9 and 10x10 fuel designs. Table 5-6 summarizes the axial power sensitivities of GEXL correlations for 9x9 and 10x10 fuels.

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

	9x9 Fuel				**10x10 Fuel**			
	GE11/GEXL07		**GE13/GEXL09**		**GNF2/GEXL17**		**GNF3/GEXL21**	
	Mean	**σ**	**Mean**	**σ**	**Mean**	**σ**	**Mean**	**σ**
[[								
								]]

[[

]]

5.7 GEXL21 Correlation Statistics

The final statistics of the GEXL21 correlation derived from GNF3 data are shown in Table 5-7. The final correlation mean and standard deviation used for the SLMCPR process are listed in Table 5-8.

Table 5-7 GEXL21 Correlation Mean and Uncertainty from GNF3 Data

	[[
	]]

Table 5-8 GEXL21 Correlation Mean and Uncertainty for SLMCPR Process

	[[
	]]

The effects of APS on the critical power predicted by GEXL21 were evaluated using the GNF3 [[ ]] The comparisons show that GEXL21 power shape effects are adequately predicted compared to Stern data and consistent with the trend observed for previous fuel designs as shown in Table 5-6. The following observations can be made from the table:

- [[

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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 SLMCPR; the determination of the transient change in CPR during AOOs and the determination of the corresponding OLMCPR; and 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 SLMCPR, 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. [[

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The SLMCPR 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 SLMCPR 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 (delta CPR (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 OLMCPR 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 (LOCAs) and anticipated transients without scram (ATWS), the GEXL correlation is used to determine the condition when boiling transition and subsequent fuel heatup will occur.

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 GEXL21 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 GEXL21 is accomplished by comparing the change in CPR 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 without recirculation pump trip (TTNRPT), the flow is kept constant. 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. For a turbine trip event with recirculation pump trip (TTRPT), the flow is initially kept constant and then decreased to simulate the effect of pump trip on core flow. A third transient test type simulates a FFT event. This type is similar to the TTRPT but with a more severe flow transient and power spike, which was observed during a typical loss of stator cooling event. A fourth transient test type simulates an abrupt reduction in core flow following an APT event in internal pump plants. Typical test conditions for all four event types are shown in Figure 6-1. Also shown are temperature traces from peak and average rod 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 GEXL21 correlation, four types of transient tests were performed in the manner described above. The experimental conditions are summarized in Table 6-1. Compared to previous fuels, the transient test matrix was significantly expanded to characterize the GEXL correlation for wide ranges of transient conditions. The expanded test matrix includes more initial flow and inlet subcooling conditions, targeting different rod positions, targeting the same rod positions with different radial peaking distributions, different energy input during power spikes, different timing between power spike and flow reduction, and different amounts of flow reduction.

A comparison of calculated versus measured results is summarized in Figure 6-2 along with a comparison of calculated versus measured time to boiling transition in Figure 6-3. These results show that the GEXL21 correlation [[

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Table 6-1 Typical GNF3 Transient Test Conditions

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Figure 6-1 Test Responses for Four Transient Event Types

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Figure 6-1 Test Responses for Four Transient Event Types (Continued)

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Figure 6-2 Transient ΔCPR/ICPR Comparison

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Figure 6-3 Time to Boiling Transition Comparison

7.0 GNF3 GEXL21 Critical Power Evaluation

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 2. The ability of the GEXL correlation to accurately predict the critical power performance of BWR fuel is demonstrated by the comparisons in Reference 2 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 GEXL21 correlation was developed from data obtained in full-scale critical power simulations of GNF3 10x10 fuel assemblies having reactor grade spacers. This section provides the results of the analyses performed to demonstrate the application of the final GNF3 GEXL21 correlation to predict the GNF3 test data.

A statistical analysis was performed for the GNF3 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 GNF3 GEXL21 correlation is considered valid, as identified in Section 5.4. To facilitate the statistical evaluation of the predictive capability of the GNF3 GEXL21 correlation, the concept of an ECPR is used. The ECPR is determined from the following relationship:

$$ECPR \equiv \frac{\text{Predicted Critical Power}}{\text{Measured Critical Power}} \tag{7-1}$$

Figure 7-1 shows the frequency distribution of all ECPRs for GEXL21 versus test data results for GNF3. [[

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In summary, critical power data recorded under simulated reactor operating conditions with GNF3 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.

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Figure 7-1 Frequency versus ECPR Histogram for GNF3 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 GEXL21 R-factor calculation process is consistent with the methodology submitted to the Nuclear Regulatory Commission (NRC) and accepted as part of the GE reload licensing application (Reference 4). The validity of this methodology for GNF3 fuel is confirmed by virtue of the adequacy of the GEXL21 correlation statistics and trend characteristics that are based on Stern Laboratories test data.

8.2 R-Factor Calculational Process

Local two-dimensional (2D) 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 2D 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. [[

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

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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 2D radial distributions as a function of axial height.

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- 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 GNF3 fuel. The corresponding numbers are listed in Table 8-1.

8.4 R-Factor Distribution

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The R-factor for the i^{th} rod is calculated from the equation:

[[ ]] (8-1)

where:

[[

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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),

[[ ]] (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)

A summary of the R-factor calculational method for each GNF3 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 8-7 for any specified fuel assembly exposure, control state and channel bow.

$$R = \overline{Max}\left[R_i\right] \qquad \text{taken over all } i \tag{8-7}$$

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Figure 8-1 GNF3 Axial Shapes for Rod Power Integration

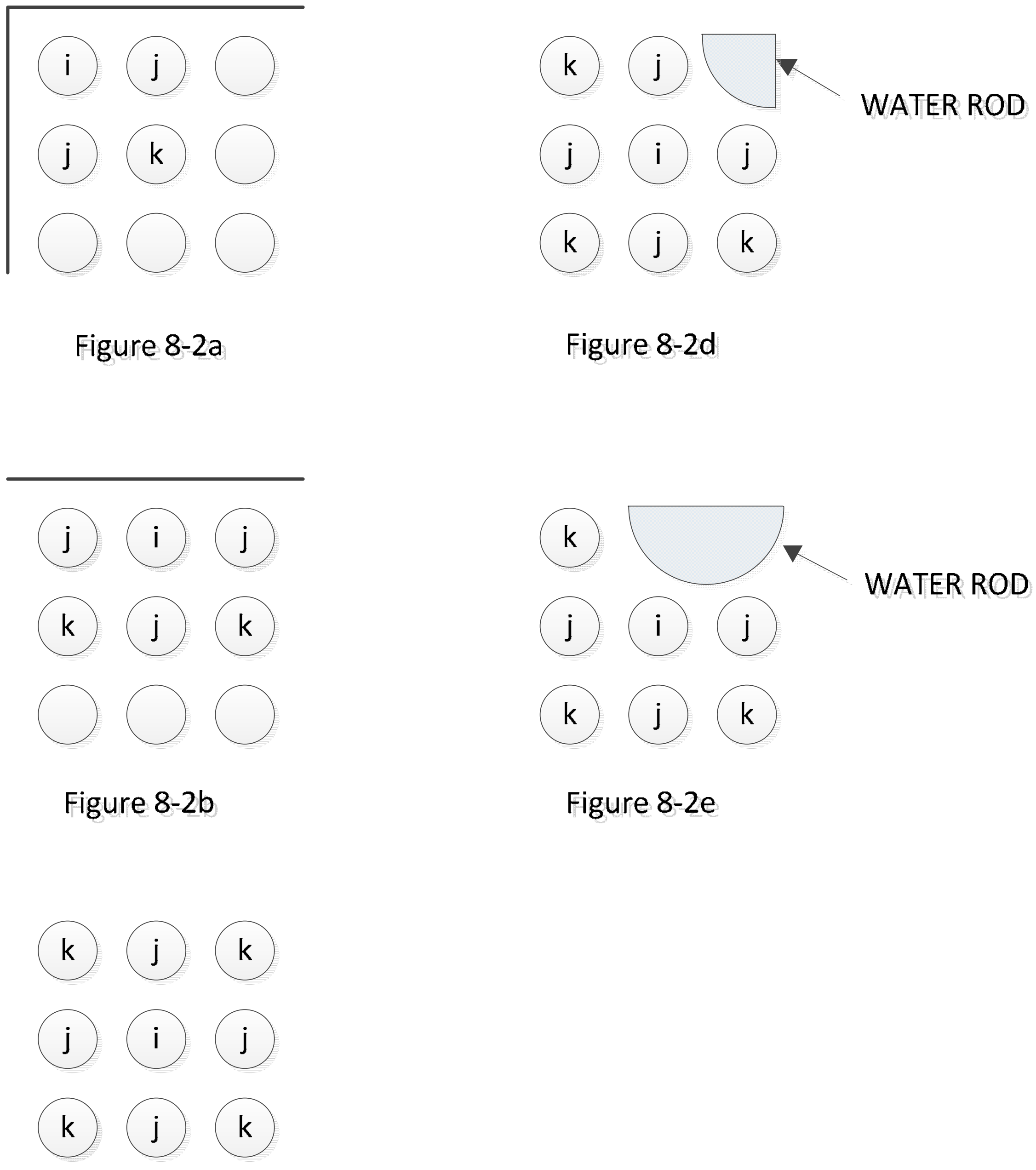

Figure 8-2a

Figure 8-2d

Figure 8-2b

Figure 8-2e

Figure 8-2c

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

Table 8-1 GNF3 Axial Shapes for Rod Power Integration

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													]]

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	8-2c	8-4
4,4	8-2d	8-5
4,5	8-2e	8-6

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 Equation 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

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4. GE Nuclear Energy, “R-Factor Calculation Method for GE11, GE12, and GE13 Fuel,” NEDC-32505P-A, Revision 1, July 1999.