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Attachment 5

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GEXL97 Correlation Applicable to ATRIUM-10 Fuel
Non-Proprietary Version

Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

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June 2008

GEXL97 Correlation Applicable To ATRIUM-10 Fuel

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Document Title: GEXL97 Correlation Applicable To ATRIUM-10 Fuel
June 2008

ABSTRACT

The GEXL97 correlation for determining the minimum critical power ratio (MCPR) during normal and transient operation for the boiling water reactor (BWR) and its development is presented for application to the AREVA ATRIUM-10 fuel design. 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 database used to support the development of the GEXL97 correlation consisted of calculated critical power data generated with the corrected SPCB critical power correlation as encoded in AREVA's thermal-hydraulic model XCOBRA. The specific ATRIUM-10 GEXL97 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 GEXL97 correlation is used to determine the expected thermal margin for the ATRIUM-10 fuel in the operating cycle. Thermal margins for the Global Nuclear Fuel (GNF) bundles in the operating cycle will be determined based on the appropriate GEXL correlation for those fuel designs. In the safety analysis process the GEXL97 correlation is to be applied to the ATRIUM-10 fuel in the mixed core while the appropriate GNF GEXL correlation will be applied to the GNF fuel (including the determination of an acceptable MCPR safety limit for the mixed core). Based on the supporting SPCB correlation generated database, it is concluded that the safety related conditions have been satisfied with respect to the development of an acceptable critical power correlation.

The overall uncertainty of the GEXL97 correlation in prediction of the critical power for ATRIUM-10 fuel is [[

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TABLE OF CONTENTS

	Page
1. INTRODUCTION AND SUMMARY	**1-1**
2. CRITICAL POWER DATABASE FOR GEXL97	**2-1**
3. DATA COLLECTION MATRIX AND CORRELATION PROCEDURES	**3-1**
3.1 THE ATRIUM-10 DATA COLLECTION MATRIX	3-1
3.2 CORRELATION PROCEDURE FOR GEXL97	3-1
3.3 GEXL97 CORRELATION	3-3
4. CRITICAL POWER CORRELATION	**4-1**
4.1 FORM OF THE GEXL CORRELATION	4-1
4.2 GEXL97 APPLICATION RANGE	4-3
4.3 CALCULATION OF CRITICAL POWER BY GEXL	4-4
4.4 GEXL INPUT PARAMETERS	4-5
4.4.1. Boiling Length	*4-5*
4.4.2. Thermal Diameter	*4-5*
4.4.3. Mass Flux	*4-6*
4.4.4. Pressure	*4-6*
4.4.5. R-Factor	*4-6*
4.4.6. Annular Flow Length	*4-6*
5. ATRIUM-10 GEXL97 CRITICAL POWER EVALUATION	**5-1**
6. NOMENCLATURE	**6-1**
7. REFERENCES	**7-1**
APPENDIX A. R-FACTOR CALCULATION METHOD	**A-1**
A.1 INTRODUCTION	A-1
A.2 R-FACTOR CALCULATION PROCESS	A-1
A.3 BUNDLE AVERAGE AXIAL DISTRIBUTIONS	A-1
A.4 R-FACTOR DISTRIBUTION	A-3
A.5 R-FACTOR CALCULATION EXAMPLES	A-3
A.6 FUEL ASSEMBLY R-FACTOR	A-4

LIST OF TABLES

Table Title Page

TABLE 2-1. GEXL97 DATABASE FOR ATRIUM-10 FUEL 2-2
TABLE 2-2. GEXL97 DATABASE DETAILS 2-3
TABLE 2-3. ATRIUM-10 MODELING DIMENSIONS 2-5
TABLE 3-1. ATRIUM-10 CRITICAL POWER DATA MINIMUM COLLECTION MATRIX (STEADY-STATE) 3-2
TABLE 3-2. STATISTICAL SUMMARY FOR ATRIUM-10 GEXL97 3-3
TABLE 3-3. STATISTICAL SUMMARY FOR EACH AXIAL POWER SHAPE FOR ATRIUM-10 GEXL97 3-3
TABLE 4-1. GEXL97 CORRELATION COEFFICIENTS 4-2
TABLE 4-2. GEXL97 ADDITIVE CONSTANTS FOR ATRIUM-10 FUEL 4-6
TABLE 5-1. STATISTICAL SUMMARY FOR COMBINED GEXL97 AND SPCB UNCERTAINTY 5-4
TABLE 6-1. NOMENCLATURE 6-1
TABLE 6-2. ACRONYMS 6-3
TABLE A-1. R-FACTOR CALCULATION BY LATTICE POSITION A-6
TABLE A-2. ATRIUM-10 AXIAL SHAPES FOR ROD POWER INTEGRATION A-8

LIST OF ILLUSTRATIONS

Figure Title Page

FIGURE 2-1. ATRIUM-10 ASSEMBLY ROD NUMBERING SYSTEM 2-4
FIGURE 2-2. BUNDLE AXIAL POWER SHAPES - AREVA CRITICAL POWER DATA COLLECTION 2-6
FIGURE 3-1. SPCB CALCULATED VS. GEXL97 CALCULATED CRITICAL POWER 3-4
FIGURE 3-2. GEXL97 MASS FLUX TRENDS 3-4
FIGURE 3-3. GEXL97 PRESSURE TRENDS 3-5
FIGURE 3-4. GEXL97 INLET SUB-COOLING TRENDS 3-5
FIGURE 4-1. GEXL97 R-FACTOR TRENDS 4-3
FIGURE 4-2. CRITICAL POWER ITERATION SCHEME 4-5
FIGURE 4-3. REGIMES OF TWO-PHASE FLOW 4-8
FIGURE 5-1. FREQUENCY VERSUS ECPR HISTOGRAM FOR ATRIUM-10 GEXL97 5-4
FIGURE 5-2. COMPARISON OF INTEGRATED PROBABILITY OF BOILING TRANSITION 5-5
FIGURE A-1. ATRIUM-10 AXIAL SHAPES FOR ROD POWER INTEGRATION (NORMALIZED) A-2
FIGURE A-2. IDENTIFICATION OF RODS IN POSITIONS ADJACENT TO ROD I A-5
FIGURE A-3. ATRIUM-10 LATTICE A-7

1. INTRODUCTION AND SUMMARY

This report summarizes the development of the ATRIUM-10 GEXL97 correlation. The ATRIUM-10 GEXL97 correlation will be used to determine the critical power performance of the AREVA ATRIUM-10 fuel in a mixed core of AREVA and GNF fuel. This document describes the process used in the development of the GEXL97 correlation for prediction of critical power for ATRIUM-10 fuel and the determination of the overall uncertainty of that correlation in prediction of the ATRIUM 10 critical power performance.

ATRIUM-10 calculated bundle critical power data was obtained from AREVA based on the SPCB correlation (Reference 2, 3) as encoded in the AREVA thermal hydraulic model XCOBRA. Subsequent to NRC approval, AREVA identified an error in the SPCB correlation applicable to ATRIUM-10 fuel. The error involved the calculation of the local power peaking distribution for the test assemblies used to determine critical power performance. AREVA has corrected the error (Reference 3), and the data used in this report are based on this error correction. The objective of this data collection was to obtain quality data appropriate for GEXL analysis. The span of the data collection encompasses cosine, top peaked, bottom peaked, and double humped axial power shapes in order to cover the complete range of expected operation of the ATRIUM-10 fuel in a BWR core. The data was used to develop a new GEXL correlation for the ATRIUM-10 design. This new GEXL correlation for ATRIUM-10 fuel is designated as GEXL97. The new GEXL97 correlation uses the same functional form as previous GEXL correlations with different constants for the GEXL correlation coefficient parameters. This report provides the results of the GEXL97 correlation development, including the overall uncertainty relative to measurement results.

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 necessary for determining the MCPR operating limits resulting from transient analysis, the MCPR safety limit analysis, and the core operating performance and design. The GEXL correlation is an integral part of the transient analysis methodology. 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 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.

The GEXL correlation was originally developed based on test data typical of 7x7 and 8x8 fuel assemblies. Over 14,000 data points having various numbers of rods, heated lengths, axial heat flux profiles, and rod to rod power distributions were used in the development of the original GEXL (GEXL01) correlation. The boiling transition test data available at the time of the development of the GEXL01 correlation are provided in the original licensing topical report (Reference 1). Further background on the development of the GEXL97 correlation is provided in Section 2.

The GEXL correlation requires the development of coefficients for the specific mechanical geometry of the fuel assembly design. The database supporting the development of the GEXL97 correlation is described in Sections 2 and 3.

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. The exact form of the GEXL correlation and the coefficients for ATRIUM-10 fuel are provided in Section 4.

The measure of the capability of a boiling transition prediction correlation is its ability to predict the collected data. The GEXL correlation has been demonstrated to be an accurate predictor of the data generated from the SPCB ATRIUM-10 critical power correlation. Its capability for predicting ATRIUM-10 fuel is provided in Sections 3 and 5. The nomenclature and references used in this report are demonstrated in Sections 6 and 7, respectively.

The overall uncertainty of the GEXL97 correlation in prediction of the critical power for ATRIUM-10 fuel is [[ ]]

2. CRITICAL POWER DATABASE FOR GEXL97

The current form of the 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 primary source of boiling transition data used in the development and verification of the GEXL correlation are dryout tests at the GE ATLAS facility in San Jose, California. The ATLAS test loop generates pressure, flow and temperature conditions that accurately simulate the actual operating reactor environment.

The data for the GEXL97 development specific to ATRIUM-10 fuel was generated using the SPCB correlation (Reference 2, 3). Specified rod-to-rod peakings, axial power shapes, pressure, mass flux and sub-cooling were used in the AREVA thermal hydraulic model XCOBRA with the SPCB correlation to determine critical power at dryout. No GEXL97 development data was generated outside the SPCB correlation range of applicability.

ATRIUM-10 fuel is a 10x10 fuel bundle with a water channel design that displaces 9 fuel rods. It contains a total of 83 full-length fuel rods and 8 part length rods. It has 27 unique fuel rod locations (Figure 2-1) within the 10x10 lattice for which dryout data was collected. In Section 4, the final GEXL97 correlation for ATRIUM-10 fuel is given, including additive constants. The database used in the development of the GEXL97 correlation for ATRIUM-10 fuel is summarized in Table 2-1. This table shows the number of calculated critical power data points obtained using the SPCB critical power correlation for cosine, inlet, outlet, and double humped axial power distributions. It also shows the fuel pin dryout location that formed the basis of the 28 different sets of AREVA calculated critical power data. Table 2-2 shows the same information but further divides the data collected into subgroups of pressure, mass flux, and inlet sub-cooling.

The ATRIUM-10 modeling dimensions used in the AREVA generation of the SPCB dryout data as well as in the development of the GEXL97 correlation are provided in Table 2-3. The generated data was based on chopped cosine, top and bottom, and a double humped peaked axial power profile. The axial power profiles are shown in Figure 2-2.

Table 2-1. GEXL97 Database for ATRIUM-10 Fuel

Data Set	Number of Critical Power Data Points				Fuel Pin Dryout Position
	[[			]]	
[[					
				]]

Table 2-2. GEXL97 Database Details

		Nominal Thermal Hydraulic Conditions																									
Collection Type	Axial Shape	Pressure (psia)										Mass Flux (Mlb/hr-ft2)									Inlet Subcooling (Btu/lbm)						
[[																											

]]

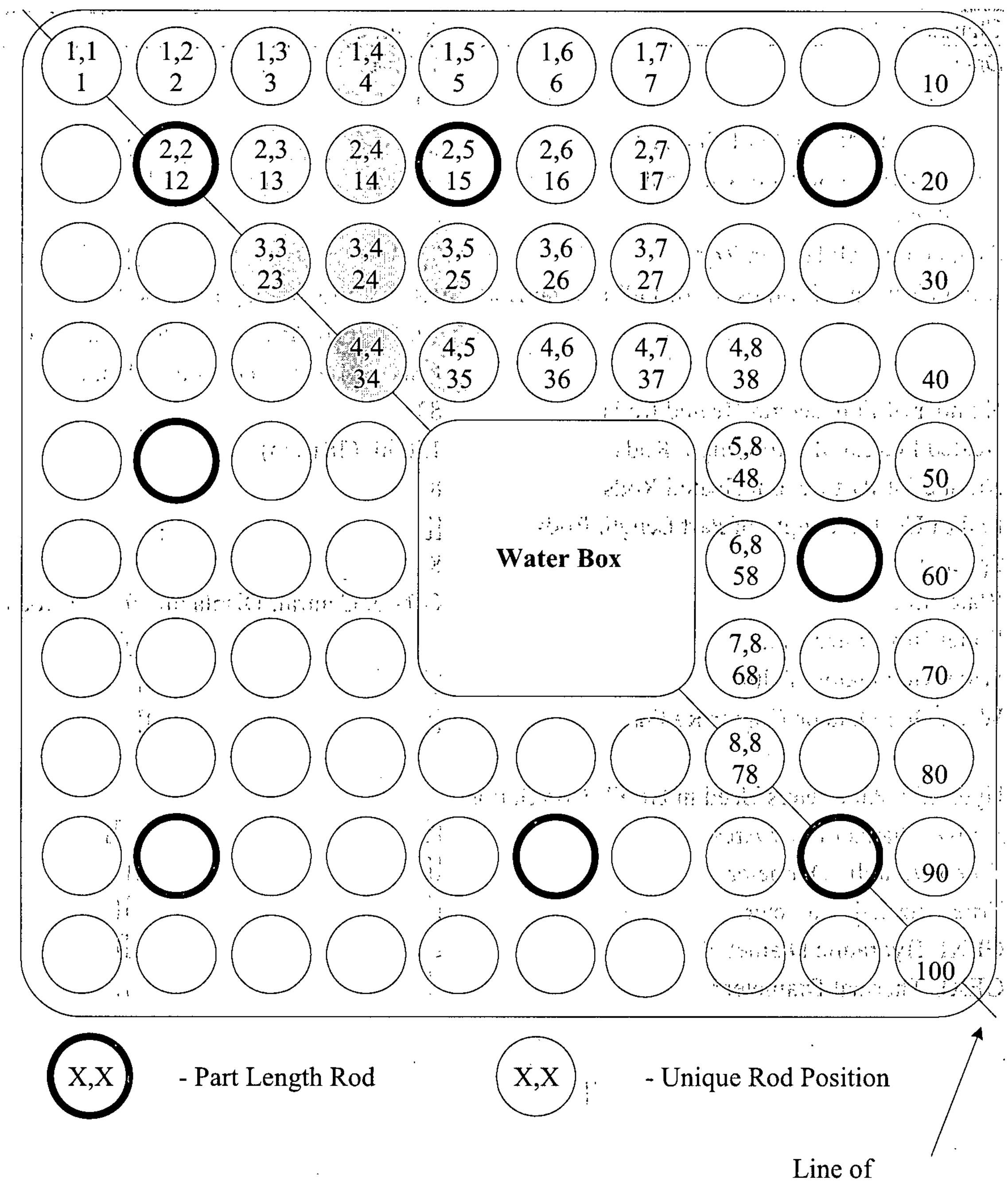

Figure 2-1. ATRIUM-10 Assembly Rod Numbering System

Table 2-3. ATRIUM-10 Modeling Dimensions

Characteristic	Assembly
Data sets	1 through 28
Lattice	10 x 10
Nominal Inside Width of Channel	[[ ]]
Inside Corner Radius of Channel	[[ ]]
Rod Pitch	[[ ]]
Diameter of All Heated Rods	[[ ]]
Axial Heat Flux Profiles (4) of Full Length Rods	1.4 Peak-to-Average Cosine 1.6 Peak-to-Average Bottom and Top Peaked, 1.2 Peaked Double Humped
Number of Full Length Heated Rods	83
Heated Length of Full Length Rods	150 in. (381 cm)
Number of Part Length Heated Rods	8
End of Heated Length of Part Length Rods	[[ ]]
Spacers	8
Water Box	Off-set Central, Displacing 9 Fuel Rods
Water Box Outer Area	[[ ]]
Water Box Outer Width	[[ ]]
Water Box Outside Corner Radius	[[ ]]
Hydraulic Parameters Used in GEXL Correlation:	
Active Channel Flow Area	[[ ]]
True Hydraulic Diameter	[[ ]]
True Thermal Diameter	[[ ]]
GEXL Hydraulic Diameter*	[[ ]]
GEXL Thermal Diameter*	[[ ]]

[[ ]]

[[

]]

Figure 2-2. Bundle Axial Power Shapes - AREVA Critical Power Data Collection

3. DATA COLLECTION MATRIX AND CORRELATION PROCEDURES

3.1 THE ATRIUM-10 DATA COLLECTION MATRIX

The ATRIUM-10 data collection matrix is outlined in detail in Table 3-1. This matrix shows the minimum range of data required for the GEXL97 correlation development. The data was generated by AREVA based on the SPCB correlation (Reference 2, 3) as encoded in the AREVA thermal hydraulic model XCOBRA. [[

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[[

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3.2 CORRELATION PROCEDURE FOR GEXL97

The procedure used for development of the ATRIUM-10 GEXL97 correlation can be summarized as follows:

- A range of generated data covering all parameter variations was selected to form a development database. This is the majority of the data. A separate set of data was used as the verification database.
- The correlation coefficients were chosen to minimize the bias and standard deviation in correlating the data and to minimize any trend errors in reference to flow, pressure, sub-cooling, and R-factor.
- Once the optimum coefficients were determined, the apparent R-factors were calculated for each assembly. The apparent R-factor is defined as that R-factor which yields an overall ECPR of 1.0 for a given assembly. In this document, ECPR is defined as the ratio of the GEXL97 calculated critical power to the SPCB calculated critical power.
- [[

  ]]

These steps were taken to optimize GEXL97 for the ATRIUM-10 fuel design and to minimize the prediction uncertainty. This identical process is used when developing GEXL correlation coefficients for GNF/GE fuel designs using test data.

Table 3-1. ATRIUM-10 Critical Power Data Minimum Collection Matrix (Steady-state)

Collection Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet sub-cooling:	[[
Collection Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet sub-cooling:	
Collection Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet sub-cooling:	
Collection Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet sub-cooling:	
Collection Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet sub-cooling:	
Collection Type: Number of peaking patterns: Axial Heat Flux Shape: R-factor: Pressure: Mass flux: Inlet sub-cooling:	]]

3.3 GEXL97 CORRELATION

Figure 3-1 shows the ATRIUM-10 SPCB calculated critical power data versus the calculated critical power for ATRIUM-10 fuel using the GEXL97 correlation developed herein. The final ATRIUM-10 GEXL97 correlation coefficients and additive constants are shown in Section 4. The GEXL97 correlation is developed from the majority of the data that consists of [[ ]] points for 25 different local peaking patterns and 4 axial power shapes with R-factors ranging up to [[ ]]. The overall statistics for the GEXL97 correlation are shown in Table 3-2 and Table 3-3. Figures 3-2 through 3-4 show the ECPR mean and standard deviation for mass flux, pressure, and inlet sub-cooling for the correlation database which included all collection types except high R-factor (discussed below), all axial heat flux shapes, and pin peaking patterns which were used explicitly in the GEXL97 uncertainty calculation ([[ ]] data points). The low mass flux data ([[ ]] Mlb/hr-ft^2), which had a [[ ]] mean ECPR ([[ ]]) and small uncertainty ([[ ]]), were also not included as part of the correlation development database. Figure 3-2 includes data for mass fluxes in the range of [[ ]] Mlb/hr-ft^2, Figure 3-3 includes data for pressures in the range of [[ ]] psia, and Figure 3-4 includes data for inlet sub-cooling in the range of [[ ]] Btu/lb. These figures demonstrate that there are no substantial trend errors in the GEXL97 correlation and that the GEXL97 correlation closely replicates the SPCB correlation over the given ranges.

The GEXL97 correlation was separately assessed against high R-factor data with R-factor values up to [[ ]], and a mean ECPR of [[ ]] and a standard deviation of [[ ]] were obtained. [[ ]] High R-factors in this range are generally obtained for controlled bundles, which are non-limiting bundles, and therefore these data are not included in the correlation statistics.

Table 3-2. Statistical Summary for ATRIUM-10 GEXL97

	Total Correlation Database	Development Database	Verification Database
Number of data points	[[		
Mean ECPR			
Standard deviation, σ (%)			]]

Table 3-3. Statistical Summary for Each Axial Power Shape for ATRIUM-10 GEXL97

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

[[

]]

Figure 3-1. SPCB Calculated vs. GEXL97 Calculated Critical Power

[[

]]

Figure 3-2. GEXL97 Mass Flux Trends

[[

]]

Figure 3-3. GEXL97 Pressure Trends

[[

]]

Figure 3-4. GEXL97 Inlet Sub-cooling Trends

4. CRITICAL POWER CORRELATION

4.1 FORM OF THE GEXL CORRELATION

As discussed in Section 2, the critical quality versus boiling length plane was chosen by GE as the coordinate system for correlating the boiling transition data described in Section 3. This approach was chosen because (1) it yields good precision, (2) is conceptually simple to apply, and (3) will account for variations in the 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:

$$X_C = f(L_B, D_Q, G, P, R, L_A) \tag{4-1}$$

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	= Bundle 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:

[[ ]] (4-2)

where the correlation parameters, V(I), and the coefficients, A(I), are shown in Table 4-1. The additive constants are shown in Table 4-2.

Table 4-1. GEXL97 Correlation Coefficients

[[

]]

4.2 GEXL97 APPLICATION RANGE

The GEXL97 correlation for ATRIUM-10 fuel is valid over the range stated below:

Pressure: [[
Mass Flux:
Inlet Sub-cooling:
R-factor:]]

The correlation database spanned all application ranges and is bounded by the SPCB correlation ranges of applicability.

A study of the GEXL97 trends shows that the R-factor trend is [[ ]] over the entire range of expected operation (see Figure 4-1).

[[

]]

Figure 4-1. GEXL97 R-factor Trends

[[

]] Based on these

arguments, the GEXL97 correlation can be used to perform critical power calculations for these non-limiting fuel assemblies even though their mass flux values may be greater than the upper mass flux limit specified herein.

As described in Section 3.3, a separate evaluation was completed using the high R-factor data to show that the correlation is well behaved at high R-factor conditions. The general trend of the GEXL97 correlation critical power calculations for high R-factor conditions follows the general trend of the AREVA predicted critical power performance for these highly peaked pin power profiles.

4.3 CALCULATION OF CRITICAL POWER BY GEXL

For steady-state conditions, critical power is predicted by an iterative procedure. Given the pressure, flow rate, inlet sub-cooling, axial power shape and fuel lattice design, a value for the critical power is assumed and the local quality and boiling length are computed for each axial node (24 nodes are assumed) using energy and mass balance relationships. The critical quality is also computed for each node using Equation 4-2. 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 4-2 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:

$$\mathrm{X(z)} = \left[\mathrm{Q(z)/W} - (h_f - h_{in})\right] / (h_g - h_f) \tag{4-3}$$

In Equation 4-3, 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.

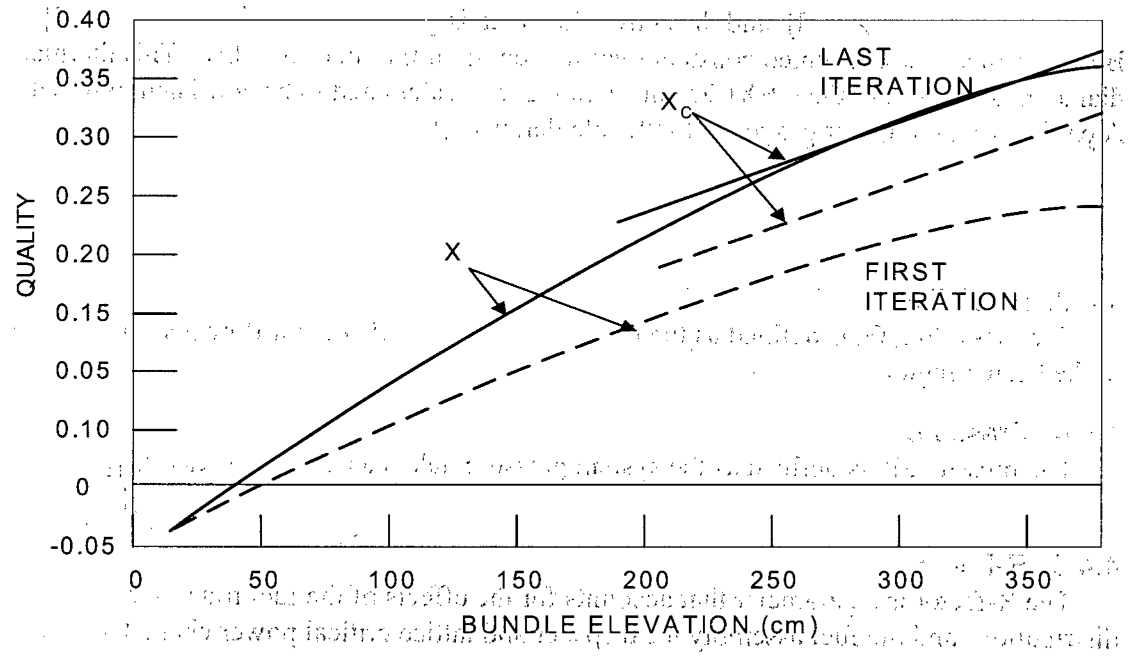

Figure 4-2. Critical Power Iteration Scheme

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 sub-cooling. 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.

4.4 GEXL INPUT PARAMETERS

This section describes the necessary inputs to the GEXL correlation for the bundle critical power calculation. Based on Equation 4-1, 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.

4.4.1. Boiling Length

Boiling length, L_B, is the distance from the onset of thermodynamic average bulk boiling to the point of boiling transition. Boiling length is not a direct input to GEXL, but it is calculated through the energy balance during the calculation of critical power described in Section 4.3. 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.

4.4.2. Thermal Diameter

The thermal diameter, D_Q, is a characteristic diameter defined in the heated length region as four times the bundle active coolant flow area divided by the total rodded perimeter, i.e. the perimeter of the fuel rods and the water box. The rodded perimeter does not include the channel. The thermal diameter used in the GEXL97 correlation for ATRIUM-10 fuel is [[ ]], and the active flow area is [[ ]]. Both parameters are assumed constant over the length of the fuel assembly. This thermal diameter is specific to the GEXL97 correlation and is calculated to be consistent with GNF-A engineering computer program (ECP) calculations. [[ ]]

4.4.3. Mass Flux

The mass flux, G, is defined as the [[ ]] coolant flow per unit flow area in the heated region.

4.4.4. Pressure

The pressure, P, is defined as the system pressure, taken as the core pressure [[ ]]

4.4.5. 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 [[ ]] A detailed description of the R-factor calculation method is provided in Appendix A. In addition, there is an additive constant applied to each fuel rod location [[ ]] For ATRIUM-10 the additive constants are provided in Table 4-2. The bolded positions represent unique rod locations for which data were generated in order to cover all symmetric locations.

Table 4-2. GEXL97 Additive Constants for ATRIUM-10 Fuel

[[

]]

4.4.6. Annular Flow Length

[[

]]

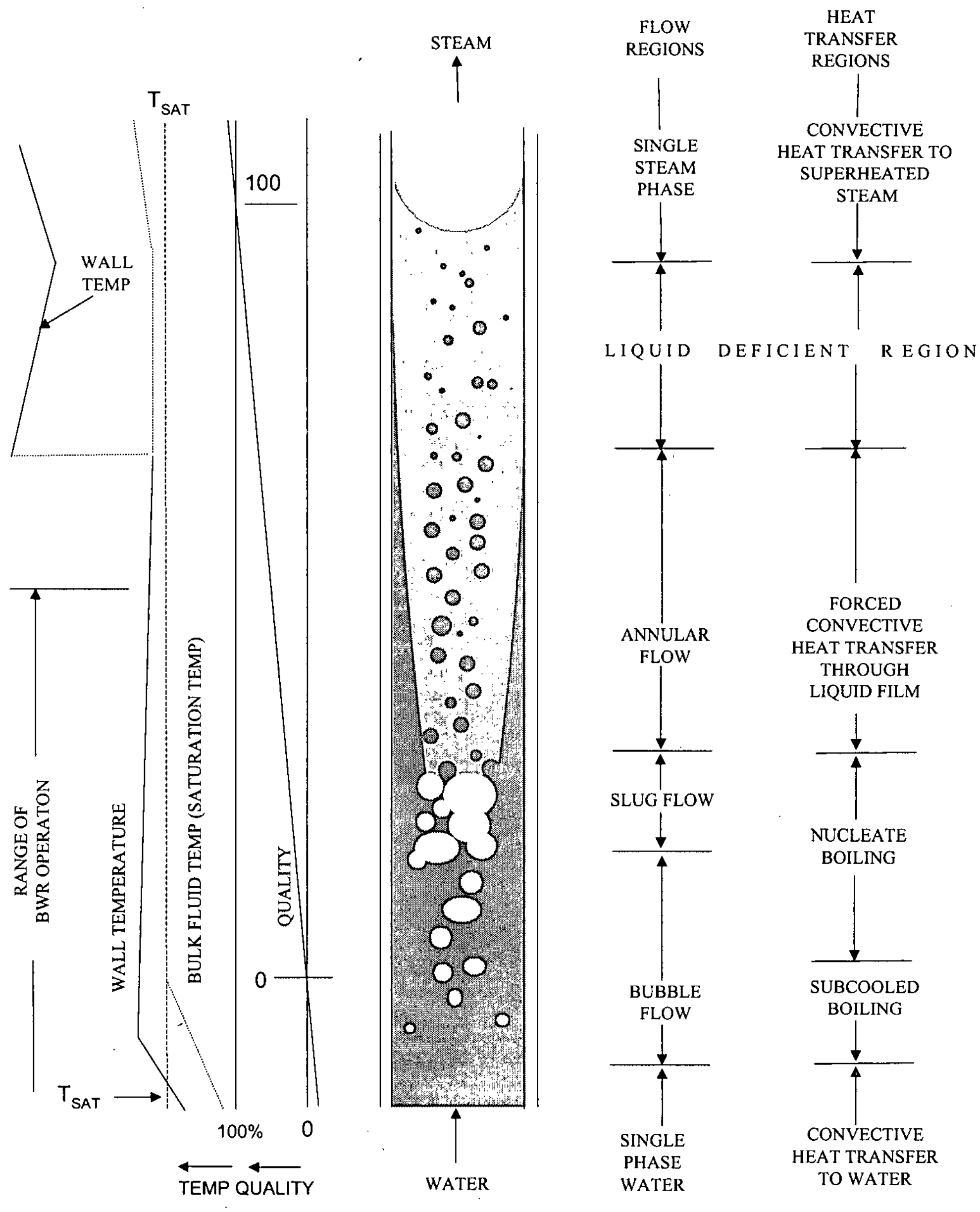

Figure 4-3. Regimes of Two-Phase Flow

5. ATRIUM-10 GEXL97 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 form of the GEXL correlation. The data covered the full range of BWR steady-state operating conditions for which an accurate prediction of critical power is an important element of the safety analysis process.

The GEXL97 correlation was developed from data generated based on the SPCB critical power correlation (Reference 2, 3) encoded in the AREVA XCOBRA thermal hydraulic model. This section provides the results of statistical analyses performed to demonstrate the application of the final GEXL97 correlation to predict the ATRIUM-10 simulated critical power data.

A statistical analysis was performed for the ATRIUM-10 correlation database consisting of [[ ]] data points for [[ ]]. The data and analyses cover the range for which the ATRIUM-10 GEXL97 correlation is considered valid, as identified in Section 4. To facilitate the statistical evaluation of the predictive capability of the ATRIUM-10 GEXL97 correlation, [[

]]

Figure 5-1 shows the frequency distribution of the calculated ECPR results for ATRIUM-10 and is a graphical representation of the ECPR results that were used to calculate the statistics shown in Tables 3-2 and 3-3. [[

]]. The large total correlation uncertainty of [[ ]] used in the safety limit calculation provides additional conservatism.

[[

]]

Table 5-1. Statistical Summary for Combined GEXL97 and SPCB Uncertainty

	Mean ECPR	Standard Deviation, σ (%)
GEXL97 Correlation	[[	
Bounding Value for SPCB Correlation		
Combined Value (Using ρ = 1)		]]

[[

]]

Figure 5-1. Frequency versus ECPR Histogram for ATRIUM-10 GEXL97

Small ECPR errors exist for the individual power shapes as shown in Table 3-3. These errors are not atypical compared to past experience and these ECPR errors are accounted for in the larger GEXL97 correlation uncertainty for the total database. The relatively small [[ ]] of the outlet and double humped axial power shapes and somewhat larger, but [[ ]] of the cosine and inlet peaked data is what leads to the non-normality of the ECPR histogram for the total database.

The safety limit is determined by summing the probability that each rod is in boiling transition and determining the point where the sum over all the rods of the probability the rod is in boiling transition equals 0.1% of the total number of rods.

$$\mathrm{NRSBT} = \sum_{\mathrm{All\,rods}} p_i = 0.001 N_R \,,$$

where: N_R is the total number of rods

p_i is the probability rod "i" is in boiling transition

NRSBT is the number of rods subject to boiling transition

For a rod "i" with a given critical power ratio, "CPR_i", the likelihood of that rod being in boiling transition is given by the probability that the ECPR is greater than the CPR value:

$$p_i = \int_{CPR_i}^{\infty} f(x)dx ,$$

where: f is the ECPR probability density function.

The impact of the non-normality can therefore be evaluated by comparing the integrated probability of boiling transition as a function of CPR value for the actual ECPR histogram and the assumed normal distribution. This comparison is shown in Figure 5-2.

[[

]]

Figure 5-2. Comparison of Integrated Probability of Boiling Transition

For the nominal conditions the limiting rod will be at the safety limit, which is typically around 1.10. All other rods will have higher CPR values. From the above figure it is clearly seen that the probability of the rods being in boiling transition is conservatively calculated when using the normal distribution.

When the uncertainties in plant operating parameters and power distribution are accounted for in the safety limit methodology, the leading bundles that contribute to the safety limit will have a CPR distribution around the safety limit. From the above figure it is seen that the probability of boiling transition is [[ ]] predicted for CPR values greater than [[ ]] and non-conservatively for CPR values between [[ ]]. Since most of the rods that contribute to the safety limit will be in the range close to the safety limit, the overall impact of using the normal distribution will be conservative.

6. NOMENCLATURE

The nomenclature and acronyms used in this report are provided below. The units shown here are general dimensions of the variables. Actual units required for dimensional calculations V (I) terms in Equation 4-2 are described in Section 4.

Table 6-1. Nomenclature

Symbol	Definition	Units
A	Bundle flow area	in^2 (m^2)
A (I)	Fuel type specific GEXL coefficients	Values in Section 4 consistent with specific English units
D_H	Hydraulic diameter	in (m)
D_Q	Thermal diameter	in (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	in (m)
L_B	Boiling length	in (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 (Pa)
q	Correction for adjacent low power rods	dimensionless

Symbol	Definition	Units
$Q(z)$	Integrated power input to the coolant up to location (z)	BTU/sec (Watts)
R	Bundle R-factor	dimensionless
R_i	R-factor for an individual rod	dimensionless
R_{FC}	R-factor at fully controlled	dimensionless
r_i	Local peaking factor for rod i	dimensionless
r_j	Local peaking factor for rod j	dimensionless
r_k	Local peaking factor for rod k	dimensionless
T	Total number of lattice positions	dimensionless
$V(I)$	GEXL correlation parameters	Values in Section 4 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)

Table 6-2. Acronyms

BWR	Boiling Water Reactor
CPR	Critical Power Ratio defined as the predicted critical power to the actual power of the particular fuel assembly, both evaluated at the same pressure, mass flux and inlet sub-cooling
ECPR	[[ ]]
ECP	Engineering Computer Program
GETAB	General Electric BWR Thermal Analysis Basis
GEXL	GE critical quality-boiling length correlation
GNF	Global Nuclear Fuels
GNF-A	Global Nuclear Fuels - Americas
MCPR	Minimum Critical Power Ratio 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
NRC	Nuclear Regulatory Commission
SPCB	AREVA (formerly Framatome Advanced Nuclear Power) critical power correlation for ATRIUM-10 fuel
XCOBRA	AREVA thermal-hydraulic model
SPC	Siemens Power Corporation

7. REFERENCES

1. NEDE-10958P-A, General Electric BWR Thermal Analysis Basis (GETAB): Data, Correlation and Design Basis, GE Proprietary Report, January 1977.
2. EMF-2209(P)(A), "SPCB Critical Power Correlation", Rev. 2, September 2003.
3. EMF-2209(NP), "SPCB Additive Constants for ATRIUM-10 Fuel", Addendum 1, Rev. 0, April 2008.
4. NEDC-32505P-A, R-Factor Calculation Method for GE11, GE12, and GE13 Fuel, Revision 1, GE Proprietary Report, July 1999.

APPENDIX A. R-Factor Calculation Method

A.1 Introduction

The R-factor is an input to the GEXL correlation 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 complete R-factor methodology is documented in Reference 4.

A.2 R-factor Calculation 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 calculation 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 individual rod R-factors.
5. Repeat these calculations for each desired bundle average exposure, control fraction and channel bow.

A.3 Bundle Average Axial Distributions

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

- [[

  ]]

- [[

  ]]

- The **bundle axial relative exposure shape** is defined as that shape which is consistent with the uncontrolled axial relative power shape assuming uniform fuel density; and

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

Figure A-1 provides a summary of these normalized axial shapes for ATRIUM-10 fuel. The corresponding numbers are listed in Table A-2.

[[

]]

Figure A-1. ATRIUM-10 Axial Shapes for Rod Power Integration (Normalized)

A.4 R-factor Distribution

[[

]] (A-1)

[[

]]

A.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 A-1. The following example is for a 10x10 lattice (ATRIUM-10).

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

Corner Rod:

Applying Equation A-1 to a corner rod (as in Figure A-2a),

[[ ]](A-2)

Side Rod:

Applying Equation A-1 to a side rod (as in Figure A-2b),

[[ ]] (A-3)

Interior Rod:

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

[[ ]] (A-4)

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

[[ ]] (A-5)

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

[[ ]] (A-6)

If there are three unheated lattice positions (as in Figure A-2f),

[[ ]] (A-7)

A summary of the R-factor calculation method for each ATRIUM-10 lattice position (as identified in Figure A-3) is given in Table A-1.

A.6 Fuel Assembly R-factor

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

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

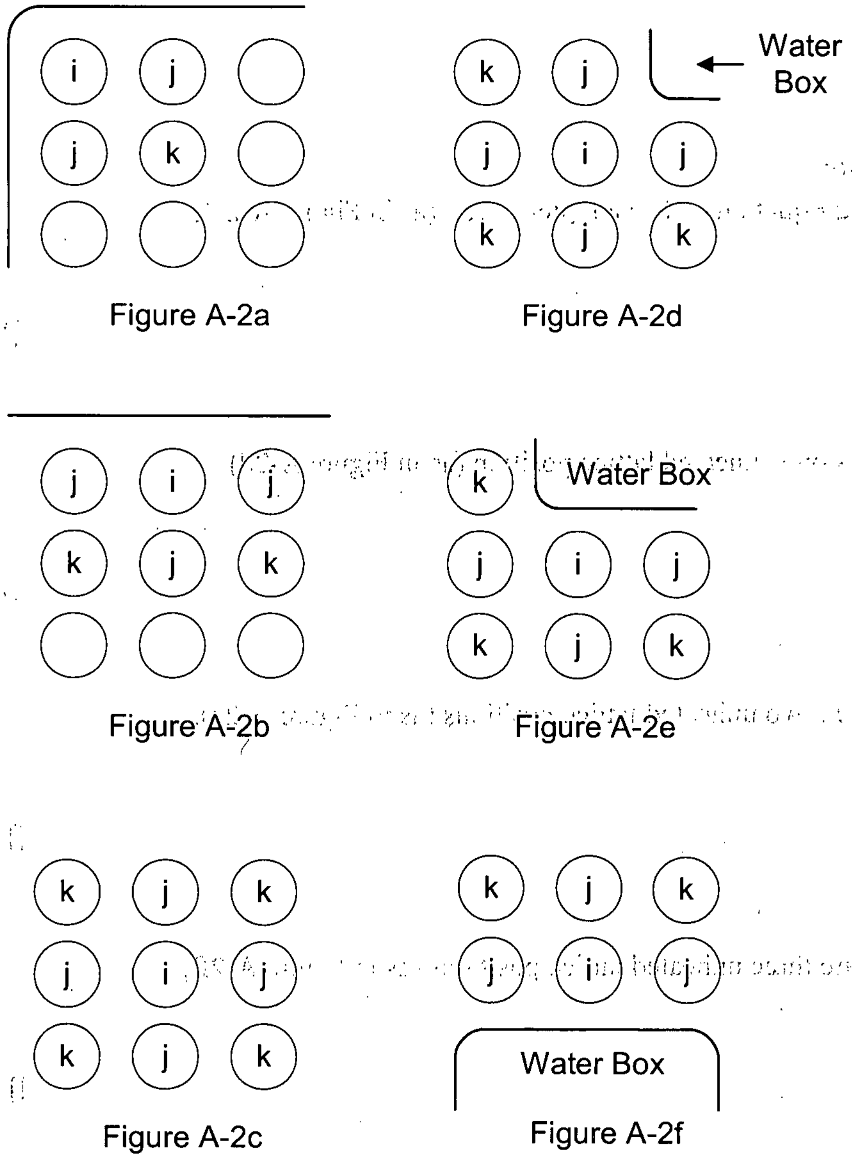

Figure A-2. Identification of Rods in Positions Adjacent to Rod i

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

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

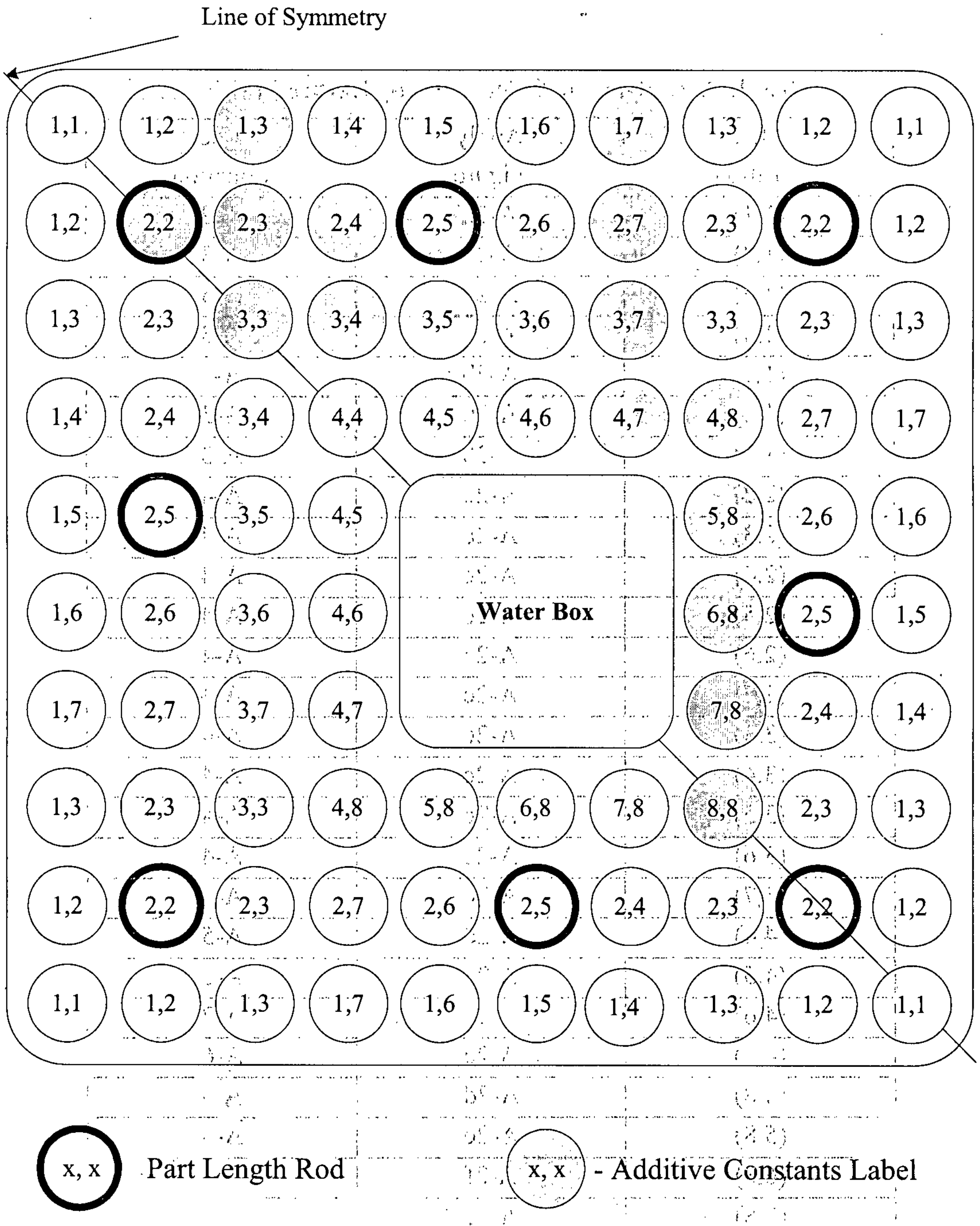

Figure A-3. ATRIUM-10 Lattice

Table A-2. ATRIUM-10 Axial Shapes for Rod Power Integration

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