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GE14 for ESBWR – Critical Power Correlation, Uncertainty, and OLMCPR Development

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1.0 INTRODUCTION

The passive safety features and natural circulation operating strategy employed in the ESBWR require a reactor core design with minimum resistance to two-phase pressure drop, while still providing sufficient density head to maintain natural circulation flow. ESBWR design optimization studies have resulted in a core bundle design, which is for the most part identical to the standard bundle design used in the BWR4/5/6 and ABWR designs except that the overall fuel bundle length has been reduced by about 27 inches and the active fuel length reduced by about 30 inches.

The GEXL critical power correlation for conventional GE14 10x10 fuel (GEXL14) has been developed using data obtained from the ATLAS critical power test facility. GE14 fuel is currently producing power in BWRs worldwide with successful operating performance. Due to the similarity between the conventional BWR and ESBWR versions of GE14, the GEXL14 correlation can be applied to ESBWR applications, provided that the geometry differences between the two versions of GE14, however small these differences are between the two versions, are quantified and properly accounted for. First, the ATLAS critical power data for the conventional BWR version of GE14 adjusted due to shortening of the heated length. A subchannel analysis model of GE14, previously qualified based on the ATLAS GE14 critical power data, is then used to quantify the effect of the geometry differences between the two GE14 versions on the critical power performance of the ESBWR version of GE14. This document discusses the application of the GEXL14 critical power correlation to ESBWR GE14 (GE14E) fuel and the supporting analyses performed to quantify and subsequently account for the effect (on critical power) of the differences between GE14 for the conventional BWRs and GE14E for ESBWR.

2.0 COMPARISON OF CONVENTIONAL (GE14) AND ESBWR (GE14E) FUEL DESIGNS

Figure 2-1 shows the GE14 fuel bundle specifying the differences between the ESBWR and conventional BWR versions. The major differences are the axial length of the fuel rods and the number of spacer grids in the bundle. Figure 2-2 shows the GE14 fuel lattice, which is the same for GE14E. Table 2-1 below is a summary of the major thermal hydraulic parameters for the GE14 ATLAS test assembly and GE14E.

Table 2-1 Summary of the Major Thermal Hydraulic Parameters for the GE14 ATLAS Test Assembly and GE14E

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Figure 2-1 The GE14 Fuel Bundle

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Figure 2-2 The GE14 Fuel Lattice

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For the purposes of evaluating critical power, the internal channel dimensions are most critical. It can be seen from Table 2-1 that the only differences between GE14 and GE14E are the overall heated length of the fuel, the length of the part length rods and the spacer positions. Figure 2-3 is a schematic illustrating these differences, all of which will be accounted for in the application of GEXL14 to GE14E.

Figure 2-3 GE14 and GE14E Schematic

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3.0 THE GEXL CORRELATION

The GEXL critical power correlation was developed in the 1970's to provide a comprehensive model for the prediction of the critical power phenomenon in BWR fuel. GEXL was first applied in GE6 fuel product line and was approved by the NRC staff in 1977 [Reference 1]. An annular flow length term was added to the correlation and the name modified to GEXL-Plus. The GEXL-Plus correlation has been applied to all GE BWR fuel products since GE11 and is now referred to as the GEXL correlation. It has been common practice to develop a new form of the correlation for each new fuel product line containing a major change in the fuel bundle geometry or spacer design. The GE14 GEXL correlation is described in Reference 2. Part of the correlation input is the R-factor, which describes the effect of individual rod power on the critical power. The procedures for R-factor evaluation are described in Reference 3.

The ATLAS facility has been used to develop the correlation data for all GE fuel designs beginning with GE6 and ending with GE14. The ATLAS facility is an electrically heated mockup of a BWR fuel bundle containing prototypical spacers and operating at BWR flows, pressures, and temperatures. For a given bundle flow, pressure, and inlet temperature the bundle power is continually increased until temperature sensors detect a sudden rise in fuel rod surface temperature. This rise indicates that the annular liquid flow near the top of the limiting fuel rod has decreased sufficiently to indicate the onset of boiling transition (dryout). This condition is known as the bundle critical power for a given set of inlet flow, temperature, and pressure conditions. This test procedure is applicable to the critical power testing of BWR fuels regardless of the coolant flow circulation mode, i.e. forced vs. natural. As the inlet flow, temperature, and pressure boundary conditions are the controlled test parameters, the mode of circulation does not play any role on the critical power data. It should also be noted that the expected fluid conditions for ESBWR fuel due to lower mass flow rates and higher thermal output conditions are enveloped by the fluid conditions achieved at critical power inside the test assembly.

The GEXL correlation does not evaluate the critical power directly. Rather it evaluates the quality at which critical power conditions occur. The critical quality is expressed as a function of six variables:

[[ ]]

where

[[ ]]

[[ ]]

[[ ]]

[[ ]]

[[ ]]

[[ ]]

[[ ]]

A detailed description of these variables can be found in Reference 2.

The bundle critical power is determined through an iterative process for a given set of conditions, as illustrated in Figure 3-1. An initial power is assumed, and the equilibrium quality X and the critical quality X_C are evaluated as functions of axial position. The bundle power is increased until there is an actual point where the [[ ]]. The dashed lines represent the initial iteration and the solid lines represent the final iteration.

Figure 3-1 Critical Power Iteration Procedure

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This procedure also yields a relative estimate, with regards to boiling length, of the axial location of dryout, since the dryout location is a strong function of the spacer position. The dryout phenomenon occurs in the annular flow region, where the fuel rods are coated with a liquid film and rest of the volume between the rods is occupied by steam and liquid droplets. Figure 3-2 shows the influence of spacers on the liquid film. In the annular flow region, the liquid film thickness decreases as the local quality increases. [[ ]]. Hence the minimum film thickness occurs [[ ]].

It can be seen from the figure above that [[ ]]. The critical power effect [[ ]] has been verified experimentally. The axial position of dryout is a function of many parameters, but as the critical quality decreases with increasing flow rate, the location of dryout tends to occur lower in the assembly.

Figure 3-2 Influence of Spacers on Liquid Film Thickness

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4.0 APPLYING GEXL14 ATLAS CRITICAL POWER DATA TO ESBWR FUEL

4.1 THE GEXL14 DATA BASE

The GEXL14 database was developed for the GE14 product to be placed in the current version of BWR3 though BWR6. It consists of [[ ]] critical power measurements obtained using a [[ ]] axial power shape with [[ ]] rod peaking distributions. An additional database exists for GEXL14 that includes [[ ]] measurements obtained using a [[ ]] axial power shape with [[ ]] rod peaking distributions and [[ ]] measurements obtained using an [[ ]] peaked axial power shape with [[ ]] rod peaking distributions. The total number of critical power measurements that support GEXL14 for GE14 is [[ ]]. The axial power shapes are shown in Figure 4-1. The application range for GEXL14 is

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Figure 4-1 GE14 ATLAS Axial Power Shapes

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4.2 MODIFICATION OF THE GEXL ATLAS DATA FOR GE14E

From a thermal hydraulic standpoint, the GE14 database and the GE14E design differ in three respects:

- The overall heated length of the bundle is shortened from [[ ]]
- The axial position of the spacers relative to one another have changed (see Figure 2-3)
- The heated length of the part length rod has changed from [[ ]] and the physical length has changed from [[ ]]

The following sections describe the procedures for adapting the GE14 data to account for the differences listed above.

4.2.1 Change in Active Fuel Length

The critical power process is determined solely by what happens upstream of the point of dryout, as illustrated in Figure 3-1. The difference between the critical quality, X_C, and the equilibrium quality, X, at any point, z, along the axial length continually decreases as z increases. This behavior allows one to conservatively determine a critical power correlation for a bundle design shorter than the one used in the critical power measurements. This is done by assuming that the critical power behavior is determined solely by the [[ ]], the length of active fuel for ESBWR. For those critical power points where dryout has occurred at spacers 3 and 4 for GE14 (see Figure 2-3), the data accurately represents a bundle with a heated length of [[ ]]. For those data where dryout occurs at spacers 1 or 2, we assume that the critical power is limited to the integrated power generated in the first [[ ]] of heated length. In reality, dryout did not occur until a higher quality, so this assumption is conservative. In order to evaluate the accuracy of the GEXL14 correlation for ESBWR fuel, a reduced critical power is constructed, i.e.,

[[ ]]

Where *APF(z)* is the axial power distribution for the data point in question. For the GE14 data base,

$CP_{GE14E}/CP_{GE14} \approx$ [[ ]] for [[ ]] axial power shape

$CP_{GE14E}/CP_{GE14} \approx$ [[ ]] for [[ ]] peak axial power shape.

This conservative procedure postulates that the first [[ ]] of active fuel length produces dryout, even though the ATLAS data shows dryout occurs at a higher level. The GEXL correlation is applied to the first [[ ]] of the ATLAS bundle to obtain the overall performance parameters.

4.2.2 Change in Spacer Locations

Changes in axial distance between spacers can affect critical power performance for reasons outlined in Section 3.0. The spacer locations for the GE14 and GE14E designs are shown in Figure 2-3. For spacers 4 and above, the relative position and spacer pitch (distance between spacers) are [[ ]] between the two designs. For GE14E, the distance between spacer 4 and 5 is [[ ]] that in the conventional design. Hence, the critical power will be slightly larger in GE14E than measured in ATLAS. This spacer difference effect has been evaluated with the subchannel program COBRAG, where a subset of the test matrix has been used to compare the GE14E spacer pitch with the GE14 spacer pitch using the GE14E fuel length.

COBRAG (see Reference 4) is a steady-state subchannel analysis code for performing analysis on BWR fuel bundles. It can be used to predict bundle critical powers and dryout locations, bundle averaged and planar local void fractions and bundle pressure drops. A description of the COBRAG model for GE14, its qualification against the ATLAS GE14 critical power data, and a study of axial power shape effect on the GE14 critical power are provided in Appendix A. First, COBRAG is used to predict the critical power of GE14 with the heated length truncated at [[ ]] for a total number of [[ ]] ATLAS test runs, mainly the data from the GE14 tests with a Cosine axial power shape. The mean and standard deviation of the ratios of COBRAG calculated vs. critical power for these test runs are [[ ]] and [[ ]], respectively. The mean and standard deviation of the COBRAG calculated vs. the measured critical power for GE14 were reported as [[ ]] and [[ ]], respectively (see Table A-1 of Appendix A). The [[ ]] increase in the mean of the calculated vs. measured critical power data ratios supports the conservatism expected due to including dryout data from Spacers 1 and 2 (see the discussion in Section 4.2.1).

Next the axial spacer locations in the COBRAG model for GE14 with the truncated heated length is adjusted to match the elevations of GE14E spacer locations. The average difference between the critical power calculated for the truncated GE14 with adjusted spacer locations and the critical power calculated for the truncated GE14 with the original spacer locations is [[ ]] with a standard deviation of [[ ]]. Therefore, it is concluded that on average the GE14E spacer configuration yields [[ ]] critical powers, spacer height differences therefore play a small role, and most importantly, use of the GEXL correlation for GE14E with no correction for spacer height is conservative.

4.2.3 Change in Part Length Rod Length

Table 2-1 gives the heated length of the part length rod as [[ ]] for GE14 and [[ ]] for GE14E. Hence the difference in the heated length is [[ ]] between the GE14 ATLAS tests and the GE14E design. The GE14 tests therefore have an additional amount of heat generated in the PLR and should indicate a slightly larger critical power than the prototypical GE14E design. The COBRAG subchannel program was used over the same subset of the test matrix as mentioned in Section 4.2.2 to evaluate the impact of the PLR length change. The average difference between the critical power calculated for the truncated GE14 with the GE14E PLRs and the critical power calculated for the truncated GE14 with the original GE14 PLRs is [[ ]] with a standard deviation of [[ ]]. It should be noted that the axial spacer pitch was restored back to that of GE14 in this study to isolate the effect of PLR length differences.. Therefore, it is concluded that on average the [[ ]] GE14E PLRs yield [[ ]] critical power with a standard deviation of [[ ]]. The effect of [[ ]] PLRs on critical power can also be evaluated by the GEXL correlation where the PLR length is reflected in GEXL through the R-factor, which depends on the bundle peaking pattern. The change in R-factor due to the PLR change yields a critical power difference of [[ ]].

The combination of the spacer pitch and PLR length change is summarized in Table 4-1. The studies presented in this section suggest a decrease in critical power performance due to the shorter PLR lengths of GE14E, which is compensated by an increase due to the new axial spacer pitch. The use of the GEXL14 for the GE14E can be easily justified considering the results showing that the percent changes in critical power due to the differences in spacer location and PLR length between GE14 and GE14E remain below the correlation uncertainty.

Table 4-1 Summary of PLR and Spacer Pitch Effects

GE14E vs. GE14 CP Difference	COBRAG	GEXL14
Spacer Pitch	[[ ]]	[[ ]]
PLR Length	[[ ]]	[[ ]]
Total (includes interaction effects)	[[ ]]	[[ ]]

The critical power data supporting the statistical information in Table 4-1 are provided in a tabulated format in Appendix B.

4.3 COMPARISON OF GEXL14 CORRELATION WITH ADJUSTED GE14 DATA

The GEXL14 correlation has been compared with the GE14 ATLAS data as modified in Section 4.2. The original GE14 ATLAS test matrix is designed to cover flow rates one would expect in BWR2 through BWR6 and ABWR, covering mass fluxes up to 2.0 $Mlb_m/hr\text{-}ft^2$. The ESBWR flow rates are lower, encompassing core flow rates up to [[ ]] $Mlb_m/h\text{-}ft^2$ and transient mass fluxes up to [[ ]] $Mlb_m/hr\text{-}ft^2$. Since the ESBWR application concentrates on mass fluxes less than [[ ]] $Mlb_m/hr\text{-}ft^2$, it is appropriate to evaluate the mean ECPR and its associated uncertainty over mass fluxes less than or equal to [[ ]] $Mlb_m/hr\text{-}ft^2$; therefore, only those data points that are at mass fluxes of [[ ]] $Mlb/hr\text{-}ft^2$ or lower ([[ ]] points of the [[ ]] points in the GEXL14 database) are considered for GE14E. It is customary to examine the distribution of calculated to measured ratios for each of the [[ ]] points in the applicable database. This ratio is the ECPR, defined by

[[ ]].

ECPRs less than 1.0 represent points for which the correlation is [[ ]] and those greater than 1.0 represent points where the correlation is [[ ]]. It is customary to compute the average ECPR and the standard deviation of the set of ECPRs for the entire population or a given part of the population. A summary of average ECPR and standard deviation of the ECPRs are given in Table 4-2. The same data are presented graphically in Figure 4-2 and Figure 4-3.

Table 4-2 Summary of ECPR Distributions

Data Description	Number of Data Points	Average ECPR	Standard Deviation
Data with mass flux less than or equal to [[ ]] Mlb$_m$/hr-ft^2	[[ ]]	[[ ]]	[[ ]]
Critical power occurring at spacer 3 or 4 and mass flux less than or equal to [[ ]] Mlb$_m$/hr-ft^2	[[ ]]	[[ ]]	[[ ]]

Figure 4-2 Calculated vs. Measured Critical Powers

[[

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Figure 4-3 GE14E ECPR Histogram

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The first data set in Table 4-2 shows the GEXL14 correlation statistics for GE14E based on the GE14 data modified for [[ ]] and limited to mass fluxes equal to or less than [[ ]]. The second data set consists of only those points where dryout occurred near spacers 3 and 4, or below [[ ]] in the ATLAS facility. Here the average ECPR is closer to [[ ]] with a standard deviation of [[ ]]. One would expect superior agreement for these points because the dryout location closely represents the expected locations in the ESBWR bundle. The average and standard deviation for this data set represent the most accurate part of the GEXL simulation.

For GE14E applications, the average and standard deviation obtained for all of the points with mass flux less than or equal to [[ ]] Mlb/hr-ft^2 will be used for Operating Limit MCPR evaluations.

4.4 SUMMARY AND CONCLUSIONS

The GEXL14 critical power correlation was developed from data collected in the ATLAS test facility for the conventional version of GE14 fuel. The ESBWR version of GE14 (GE14E) is identical to GE14, except for those features related to the axial length of the fuel, i.e.,

- The total fuel axial length
- The number and axial location of the fuel rod spacers
- The axial length of the part length rods

The GEXL14 correlation is an accurate representation of the data obtained from the ATLAS loop where the dryout point occurs at axial heights below [[ ]], the active length of the GE14E fuel. The part length rod length and spacer locations differ between the GEXL14 ATLAS data and the GE14E design. The impact of these two differences on the critical power is on the order of [[ ]]. The GEXL formulation represents a conservative model for the net impact of these two differences.

The final accuracy of the GEXL14 correlation is based on a model in which the ATLAS power is truncated at [[ ]], the axial height of the GE14E fuel, which includes the conservative application of those data where dryout occurs above [[ ]] to formulate the average ECPR and associated uncertainty.

The recommended average ECPR and associated standard deviation to be used for GE14E in ESBWR Operating Limit calculations are based on all data with mass flux less than or equal to [[ ]] $Mlb_m/hr\text{-}ft^2$. These recommended quantities are

Mean ECPR = [[ ]],
ECPR Standard Deviation = [[ ]],

for the application range of

Pressure: [[ ]]
Mass Flux: [[ ]]
Inlet Subcooling: [[ ]]
R-factor: [[ ]]

5.0 SUMMARY OF UNCERTAINTIES

5.1 INTRODUCTION

The determination of the Operating Limit MCPR (OLMCPR) above the low power setpoint (LPSP) is based on a statistical analysis code utilizing a 3D model of the core. The code produces a critical power ratio (CPR) map of the core based on steady-state uncertainties. This is coupled with the TRACG limiting AOO ΔCPR/ICPR results to determine the OLMCPR. Details of the procedure are documented in Appendix IV of Reference 1 and Section 4.6.3 of Reference 5. Random Monte Carlo selections of operating parameters based on the uncertainty ranges of manufacturing tolerances, uncertainties in measurement of core operating parameters, calculation uncertainties, the uncertainty in the calculation of the transient ΔCPR/ICPR and statistical uncertainty associated with the critical power correlations are imposed on the analytical representation of the core, and the resulting critical power ratios are calculated.

The number of rods expected to avoid boiling transition is determined for each random Monte Carlo trial based on the statistical uncertainty associated with the critical power correlation and the transient ΔCPR/ICPR. The initial MCPR during normal operation corresponds to the OLMCPR when the FCISL (99.9% of the rods are expected to avoid boiling transition) is met for a statistical combination of the trials.

This section contains a summary of uncertainty values to be used for ESBWR Operating Limit MCPR analyses. Table 5-1 contains a summary of the uncertainties to be used in ESBWR OLMCPR analyses, along with references to the section that discusses the uncertainty values. Sections 5.2 through 5.6 contain evaluations of uncertainties associated with reactor instrumentation. These uncertainties are evaluated in accordance with standard instrument channel methodologies as prescribed in Reference 7. The error methodology in Reference 7 considers the following elements:

- The entire instrument channel from primary element through computer input
- Accuracy, calibration, and drift over a realistic 30–month surveillance interval
- Influences resulting from actual plant environments and process effects

All error terms are evaluated and combined in accordance with accepted methodologies and channel errors are determined at the one sigma (1σ) level to allow for direct comparison with Table 4.1 of Reference 8.

Sections 5.7 through 5.9 contain evaluations of thermal hydraulic parameter uncertainties, and are either based on known dimensional tolerances or comparisons of calculated versus measured pressure drop data. Section 5.10 contains evaluations of the ESBWR NMS bundle power uncertainty. Section 5.11 contains evaluations of the R-Factor uncertainty. Section 5.12 contains evaluations of the transient ΔCPR/ICPR uncertainty. All these error terms are determined at the one sigma (1σ) level to allow for direct comparison, except for the critical power and transient ΔCPR/ICPR, with Tables 4.1 and 4.2 of Reference 8.

5.2 FEEDWATER SYSTEM FLOW MEASUREMENT UNCERTAINTY

Since the feedwater system flow measurement instrumentation is not expected to be unique for the ESBWR relative to current BWRs, the description and magnitude of the BWR feedwater system flow measurement uncertainty contained in Section 2.2 of Reference 6 is applicable to ESBWR. A feedwater flow one-sigma uncertainty of [[ ]] is a design requirement for ESBWR.

5.3 FEEDWATER TEMPERATURE MEASUREMENT UNCERTAINTY

Since the feedwater temperature measurement instrumentation is not expected to be unique for the ESBWR relative to current BWRs, the description and magnitude of the BWR feedwater temperature measurement uncertainty contained in Section 2.3 of Reference 6 is applicable to ESBWR. A feedwater temperature one-sigma uncertainty of [[ ]] is a design requirement for ESBWR.

Table 5-1 Summary of Uncertainties to be Used for ESBWR OLMCPR Analyses

Uncertainty Parameter	Uncertainty ±σ (%)	Reference
Feedwater System Flow Measurement	[[ ]]	Section 5.2
Feedwater Temperature Measurement	[[ ]]	Section 5.3
Reactor Pressure Measurement	[[ ]]	Section 5.4
Core Inlet Temperature Measurement	[[ ]]	Section 5.5
Total Core Flow Measurement	[[ ]]	Section 5.6
Core Neutron Monitoring System Bundle Power	[[ ]]	Section 5.10
Channel Flow Area	[[ ]]	Section 5.7
Channel Friction Factor Multiplier Uncertainty	[[ ]]	Section 5.8
Channel to Channel Friction Factor Multiplier	[[ ]]	Section 5.9
R–Factor	[[ ]]	Section 5.11
GE14E Critical Power Correlation	[[ ]]	Section 4.4
Transient ΔCPR/ICPR	[[ ]]	Section 5.12

5.4 REACTOR PRESSURE MEASUREMENT UNCERTAINTY

Since the reactor pressure measurement instrumentation is not expected to be unique for the ESBWR relative to current BWRs, the description and magnitude of the BWR reactor pressure measurement uncertainty contained in Section 2.4 of Reference 6 is applicable to ESBWR. A reactor pressure one-sigma uncertainty of [[ ]] is a design requirement for ESBWR.

5.5 CORE INLET TEMPERATURE MEASUREMENT UNCERTAINTY

Core inlet temperature is measured by redundant core inlet temperature sensors located in each LPRM assembly below core plate elevation. A core inlet temperature one-sigma uncertainty of [[ ]] is a design requirement for ESBWR.

5.6 TOTAL CORE FLOW MEASUREMENT UNCERTAINTY

The total core flow is calculated by the heat balance core flow methodology, using the core inlet temperature measurement as inputs to determine core inlet enthalpy. A total core flow one-sigma uncertainty of [[ ]] is a design requirement for ESBWR.

5.7 CHANNEL FLOW AREA UNCERTAINTY

The uncertainty in the channel flow area can be determined from the inner dimensions of the channel and the outer diameter of the fuel and water rods along with the associated manufacturing tolerances as defined by Equation 2-6 of Reference 6. Since these dimensions are identical for the GE14E 10x10 and GE12 10x10 fuel design and the manufacturing tolerances are not expected to be unique for GE14E relative to GE12, the description and magnitude of the GE12 channel flow area uncertainty contained in Reference 6 Section 2.7 is applicable to GE14E. This uncertainty may be revised utilizing GE14E design specification manufacturing tolerances.

5.8 CHANNEL FRICTION FACTOR MULTIPLIER UNCERTAINTY

The channel friction factor is used to calculate the two-phase friction pressure loss in the BWR channel. The friction factor is determined from full scale tests performed in the ATLAS test loop. These tests are described in Reference 15. These tests cover the full range of bundle power and flow expected during ESBWR operation. The pressure drop correlation has been compared to the experimental data. As described in Reference 6, the standard deviation between the ATLAS experimental data and the correlation varies with mechanical design, but is less than [[ ]]. The results in Reference 15 Section 2.1 and 2.2 support this conclusion for the ESBWR GE14 components. In addition to the two-phase pressure drop uncertainty there is a single-phase component, which covers the pressure drop between the side entry orifice and the active channel above the lower tie plate. The Reference 6 basis includes comparison of the predicted pressure drop with the plant measure pressure drop. The ESBWR side entry orifice configuration is consistent with ABWR. Comparison of measured versus predicted pressure drop for ABWR shows less bias and uncertainty than the values reported in Reference 6. The Reference 6 uncertainty of [[ ]] is bounding for ESBWR.

5.9 CHANNEL-TO-CHANNEL FRICTION FACTOR MULTIPLIER UNCERTAINTY

In addition to the total pressure drop uncertainty, a channel-to-channel pressure drop uncertainty of [[ ]] is employed to simulate non–uniformity in channel pressure drop characteristics. Originally this non–uniformity was attributed to corrosion product deposition. The total impact of corrosion products on the pressure drop is estimated to be [[ ]]. A [[ ]] variability in the corrosion product effect yields a [[ ]] uncertainty in the channel-to-channel pressure drop. In addition to the corrosion uncertainty, there is variability in the orifice loss from bundle to bundle due to changes in flow patterns below the core plate. A [[ ]] variability in the orifice loss amounts to a [[ ]] bundle to bundle uncertainty. The RMS sum of the [[ ]] corrosion product uncertainty and the [[ ]] orifice uncertainty leads to a total bundle to bundle uncertainty of [[ ]], or a [[ ]] uncertainty in total pressure drop. It is therefore conservative to assume a [[ ]] uncertainty in OLMCPR uncertainty analyses.

5.10 NEUTRON MONITORING SYSTEM BUNDLE POWER UNCERTAINTY

The ESBWR Neutron Monitoring System (NMS) is improved over previous BWR NMSs through the replacement of the conventional source range monitor (SRM) and intermediate range monitor (IRM) with the startup range neutron monitor (SRNM), the optimization of the local power range monitor (LPRM) instrument configuration, and the replacement of the conventional traversing in-core probe (TIP) system with a fixed in-core calibration system. This system utilizes Gamma Thermometers (GT) installed within the individual LPRM assemblies to provide an independent and stable indication of the local core power levels. Such local power data are then provided as input to the core monitoring system for the three-dimensional core power calculation and LPRM calibration.

The GT bundle power uncertainty for the ESBWR NMS based on gamma scan comparisons was determined to be [[ ]] as described in Table 9-15 of Reference 10. [[ ]], as documented in Section 4 of Reference 8, bounds this value and is therefore appropriate for use in ESBWR OLMCPR calculations. The performance of the nuclear models to high enrichment and high discharge exposure applications has been routinely monitored (see Reference 9).

5.11 R-FACTOR UNCERTAINTY

The current BWR approved process for evaluating the R-factor uncertainty is documented in Section 3 of Reference 6. The Reference 6 R-factor uncertainty is [[ ]]. The Reference 6 infinite lattice peaking model uncertainty of [[ ]] was confirmed for ESBWR in Reference 14. The ESBWR value was only slightly higher: [[ ]]. Other components of the R-factor uncertainty (manufacturing uncertainty and channel bow uncertainty) are expected to be no higher for ESBWR as compared to current BWRs. The R-factor uncertainty employed for ESBWR applications has been [[ ]], which is consistent with current BWR applications.

5.12 TRANSIENT ΔCPR/ICPR UNCERTAINTY

A TRACG statistical study was performed to determine the ESBWR transient bias and uncertainty in ΔCPR/ICPR for the limiting CPR Anticipated Operational Occurrence provided in Reference 12. The data are utilized to determine the bias and standard deviation in the transient ΔCPR/ICPR. This process is described in Reference 5 and is fully consistent with the NRC approved process defined by Reference 11. The limiting event for the ESBWR is Loss Of Feedwater Heating With Failure of Selected Control Rod Run-In (LFWH with SCRRI), see Section 15.2.1.1.3 of Reference 12. The results of the statistical analysis, which is consistent with the process demonstrated in Section 8 of Reference 11, for the LFWH with SCRRI event are presented in Figure 5-1 and Figure 5-2.

The nominal ΔCPR/ICPR is [[ ]] for the hot channel. The % ΔCPR/ICPR distribution is normal for the hot channel. The percent change in the ΔCPR/ICPR is the key output from the statistical analysis. In the OLMCPR analysis, a bias of [[ ]] and a standard deviation of [[ ]] are applied to the ΔCPR/ICPR distribution.

Figure 5-1 Hot Channel ΔCPR/ICPR Descriptive Statistics for LFWH with SCRRI

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Figure 5-2 Hot Channel % ΔCPR/ICPR Descriptive Statistics for LFWH with SCRRI

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5.13 ESBWR OPERATING LIMIT MCPR EVALUATION METHODOLOGY

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Figure 5-3 Calculation Procedure Basic Steps for OLMCPR Evaluations

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6.0 REPRESENTATIVE OPERATING LIMIT MCPR

The representative OLMCPR evaluations for the ESBWR were performed using NRC approved methodology in References 1 and 5. Table 5-1 summarizes the uncertainty input parameters. Table 6-1 summarizes the ESBWR results. In general, the calculated operating limit is dominated by two key steady state parameters: (1) flatness of the core bundle-by-bundle MCPR distributions as measured by MIP, and (2) flatness of the bundle pin-by-pin power/R-factor distributions as measured by RIP. Greater flatness in either parameter yields more rods susceptible to boiling transition and thus a higher calculated OLMCPR. The ESBWR core loading information is described in Section 3.1.1 Reference 14. The limiting OLMCPR case was at EOC at minimum core flow (71.7 Mlb_m/hr from Table 4.4-1b of Reference 13). The calculated MIP value for the ESBWR core using a limiting rod pattern is [[ ]]. Pin-by-pin power distributions are characterized in terms of R-factors using the NRC approved methodology (Reference 3). For the ESBWR limiting case the RIP value, considering the participation of the contributing bundles, was calculated to be [[ ]].

The representative OLMCPR value calculated for ESBWR is shown in Table 6-1. The calculated 1.28 OLMCPR for ESBWR is consistent with expectations given the ratios for MIP and RIP that have been calculated, the axial power shapes in the core, and the methodology and uncertainties applied. Based on the information and discussion presented above, it is concluded that the assumed representative OLMCPR of 1.30 (Section 15.2.6 of Reference 12) is conservative for ESBWR.

As stated in Section 15.2.1.1.3 of Reference 12, the LFWH with SCRRI event sets the OLMCPR and will be reanalyzed for each core design and SCRRI rod pattern, for the initial core and reload cores. The COL applicant will provide a reanalysis of this event for the specific initial and reload core designs.

Table 6-1 Representative OLMCPR Results

QUANTITY, DESCRIPTION	**ESBWR value**
Cycle Exposure at Limiting Point (MWd/ST)	16,000
MCPR Importance Parameter, MIP	[[ ]]
R-factor Importance Parameter, RIP	[[ ]]
MIPRIP	[[ ]]
Calculated Operating Limit MCPR	1.28
ESBWR assumed OLMCPR	1.30

7.0 REFERENCES

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6. GE Nuclear Energy, "Methodology and Uncertainties for Safety Limit MCPR Evaluations", NEDC–32601P-A, August 1999.
7. Instrument Society of America "Recommended Practice—Setpoint Methodologies", ISA–RP67.04, Part II, September 1994.
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9. GE Nuclear Energy, "Advanced Methods Power Distribution Uncertainties for Core Monitoring", NEDC-32773P Revision 1, January 1999.
10. GE Nuclear Energy, "Gamma Thermometer System for LPRM Calibration and Power Shape Monitoring", NEDE-33197P, July 2005.
11. GE Nuclear Energy, "TRACG Application for Anticipated Operational Occurrences (AOO) Transient Analyses", NEDE-32906P-A Revision 1, April 2003.
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13. GE Nuclear Energy, "ESBWR Design Control Document Tier 2 Chapter 4 Reactor", 26A6642AP Revision 1, January 2006.
14. Global Nuclear Fuel, "GE14 for ESBWR Nuclear Design Report", NEDC-33239P, February 2006.

15. GE Nuclear Energy, "GE14 Pressure Drop Characteristics", NEDC-33238P, Class III (proprietary), December 2005.

8.0 REVISION

Revision Number	Page(s)	Description of Change(s)
0	--	Initial issue.
1	1-1	Revised the second paragraph in response to RAI 4.4-25
	3-1	Revised the second paragraph in response to RAI 4.4-28
	4-1	Revised the application range for GEXL14 in response to RAI 4.4-29
	4-4 to 4-6	Revised Sections 4.2.2 and 4.2.3 in response to RAI 4.4-26
	4-9	Revised the first paragraph in response to RAI 4.4-30
	4-10	Revised the R-factor range in table to 1.25.
	5-9 to 5.14	Added Section 5.13 in response to RAI 4.4-32
	A-1 to C-22	Added Appendices A, B, and C in response to RAI 4.4-26

Appendix A A COBRAG Subchannel Analysis

Appendix B Summary of COBRAG and GEXL14 Analyses for GE14E

Table B-1 summarizes the results previously discussed in Sections 4.2.2 and 4.2.3. The first column in this table is the ATLAS critical power test run number. The second and the third columns of Table B-1 give the pressure and the mass flux for each test number, respectively. The inlet subcooling is given in column 5. The modified critical power data based on the truncated axial power profile is tabulated in column 4. Columns 6 through 9 present the results of the COBRAG calculations for each test run. Column 6 tabulates the COBRAG critical power estimate based on the GE14 bundle with the truncated axial power profile. The results shown in column 6 are used as reference case when the individual effects of the axial spacer pitch and the PLR length on the critical power performance of the GE14E are studied. The COBRAG calculated critical power with the GE14E axial spacer pitch and PLR length are given in columns 7 and 8, respectively. Finally, the combined effect of the axial spacer pitch and the PLR length of GE14E is given in column 9. The last two columns provide the critical powers predicted using GEXL14 for GE14E.

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Appendix C Modified ATLAS GE14 Data Supporting Table 4-2