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Statistical Universal Power Reconstruction with Fixed Margin Technical Specifications

AREVA NP Inc.

Non-Proprietary

Abstract

This report describes the AREVA NP online relative power distribution reconstruction and margin calculation system, which is called Statistical Universal Power Reconstruction with Fixed Margin Technical Specifications (SUPR-FMTS). This system is applicable to pressurized water reactors. The SUPR-FMTS system produces a reconstructed power distribution which is the best estimate of all available measured data. It also provides an improved method for quantifying the uncertainty in the relative power distribution. Uncertainty is broken into two components: a continuously-updated estimate of the error in the reconstructed power and a pre-calculated uncertainty due to system observability. The reconstructed power uncertainty is based on the variance between measured and calculated signals. The system observability uncertainty is based on a Monte Carlo simulation of anticipated events. The calculated power distribution is combined with the error estimates and traditional peaking penalties to provide input to a Limiting Condition of Operation power peaking margin calculation. The margin calculation is based on the best estimate of the reactor power distribution, plus uncertainty, at any given time and limits power peaking directly through continuous online power distribution monitoring.

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Nomenclature

Acronym	Definition
ADJKPV	ADJusted Kriging Process Variance
AFD	Axial Flux Difference
BE	Best Estimate
B&W	Babcock and Wilcox
CAOC	Constant Axial Offset Control
CE	Combustion Engineering
COLR	Core Operating Limits Report
COLSS	Core Operating Limit Supervisory System
CPC	Core Protection Calculator
CTP	Core Thermal Power
DNBR	Departure from Nucleate Boiling Ratio
ECCS	Emergency Core Cooling System
EFPD	Effective Full Power Day
ExC	Excore Neutron Detector
FA	Fuel Assembly
FIC	Fixed In-Core (Self-Powered Neutron) Detectors
FMTS	Fixed Margin Technical Specifications
$F_{Q_{i,j,k}}$	Pin segment peaking factor at location i,j and level k
$F_{\Delta H_{i,j}}$	Pin peaking factor at location i,j averaged over all levels
IC-DNB	Initial Condition - Departure from Nucleate Boiling
LBP	Lumped Burnable Poison
LCO	Limiting Conditions for Operation
LOCA	Loss Of Coolant Accident
LSSS	Limiting Safety System Settings
MLE	Maximum Likelihood Estimation

NRC	Nuclear Regulatory Commission
ORB	Observed Reactor Behavior
PWR	Pressurized Water Reactor
QPT	Quadrant Power Tilt
RAOC	Relaxed Axial Offset Control
RPD	Relative Power Density
SPND	Self-powered Neutron Detector
STS	Standard Technical Specifications
SUPR	Statistical Universal Power Reconstruction
TC	Thermocouple
TIP	Traveling Incore Probes
W	Westinghouse

Symbols

α	significance level
γ	detector response
ε	error
θ	a correlation parameter
μ	mean
σ	standard deviation
ϕ	a 3D response weighting factor
ω	a weighting factor
ΔI	imbalance change
ΔT	temperature difference
$\mathbf{c}_0$	a vector of covariances
df	degrees of freedom
$f(\Delta I)$	trip function based on ΔI
$g(\mathbf{x})$	core simulator output at $\mathbf{x}$
$\mathbf{h}$	a distance vector
h	enthalpy
i	an index
i, j, k	spatial coordinates of a node
$\dot{m}$	mass flow
$p(X\|p)$	probability of observation X given parameter p
q'	rate of heat generation per unit length
$\mathbf{r}(\mathbf{x}_0)$	correlation vector
t	time, a test statistic
$\mathbf{x}$	a location vector
$\mathbf{x}_0$	point being estimated
$\mathbf{x}_i$	a measured point

$\mathbf{y}$	measured data
$\hat{y}$	best estimate of relative power density
y^*	augumented power used in LCO margin monitoring
$\mathbf{C}$	a covariance matrix
C_p	specific heat capacity
$D(\mathbf{x}_0)$	domain of the model for $\mathbf{x}_0$
DA	deviation allowance
KPV	kriging process variance
$L(p\|X)$	likelihood of parameter p given observation X
M	percent margin to peaking limit
N	number of measurements
Q	rate of heat transfer
$\mathbf{R}$	correlation matrix
RPD	relative power density
T	temperature
X	a test value

1.2 *SUPR-FMTS Processing Overview*

The SUPR-FMTS system extends the previously approved FMTS methodology in several ways. A generalized method is introduced for power reconstruction and the system uncertainty is calculated dynamically for use in the margin calculation.

Kriging, a statistical method for calculating a best linear unbiased estimate, combines three dimensional power distribution measurements with core neutronic simulator output to form a reconstructed (best estimate of measured) power distribution. Peaking augmentation factors are applied to the reconstructed power to provide the measured power peaking for the FMTS calculations.

System uncertainty is calculated as a combination of measurement uncertainty, uncertainty due to observability error, and fixed uncertainty factors. Measurement uncertainty is estimated based on the kriging variance adjusted based on deviations between the measured and predicted assembly exit thermocouples and excore neutron detector measurements, where necessary. The observability error is calculated using a Monte Carlo simulator and augments the dynamic measurement uncertainty to ensure a conservative uncertainty estimate. The fixed uncertainty factors account for known potential sources of error that are inherent to the analysis procedure. The measurement uncertainty is calculated in real time, while the observability error and fixed uncertainty factors are calculated before a given reactor operating cycle.

Using the SUPR-FMTS system, the power distribution is constructed [ ] from all of the available power distribution data, and the uncertainty is estimated [ ] based on the type and amount of data available to construct that measurement. The measurement system uncertainty dynamically reflects the measured bias of the core neutronic simulator and the uncertainties are dynamically applied in performing the core power distribution Technical Specification (Tech Spec) monitoring.

1.3 *Licensing Basis Impacts and Changes to Implement SUPR-FMTS*

Figure 1-1 illustrates how SUPR-FMTS fits into the present licensing basis. This figure also provides document identifiers [1, 2, 3, 4, 5] for documents which have supported approved methodologies related to SUPR-FMTS implementation. Several things should be noted from the figure:

1. SUPR-FMTS does not delete any Technical Specification requirements nor does it obviate any present monitoring requirements.
2. SUPR-FMTS adds direct F_Q and $F_{\Delta H}$ monitoring with a set of relaxed limits for Rod Insertion, Axial Power Shaping Rod Insertion, Axial Power Imbalance, and Quadrant Power Tilt which may be used only when SUPR-FMTS is operable.

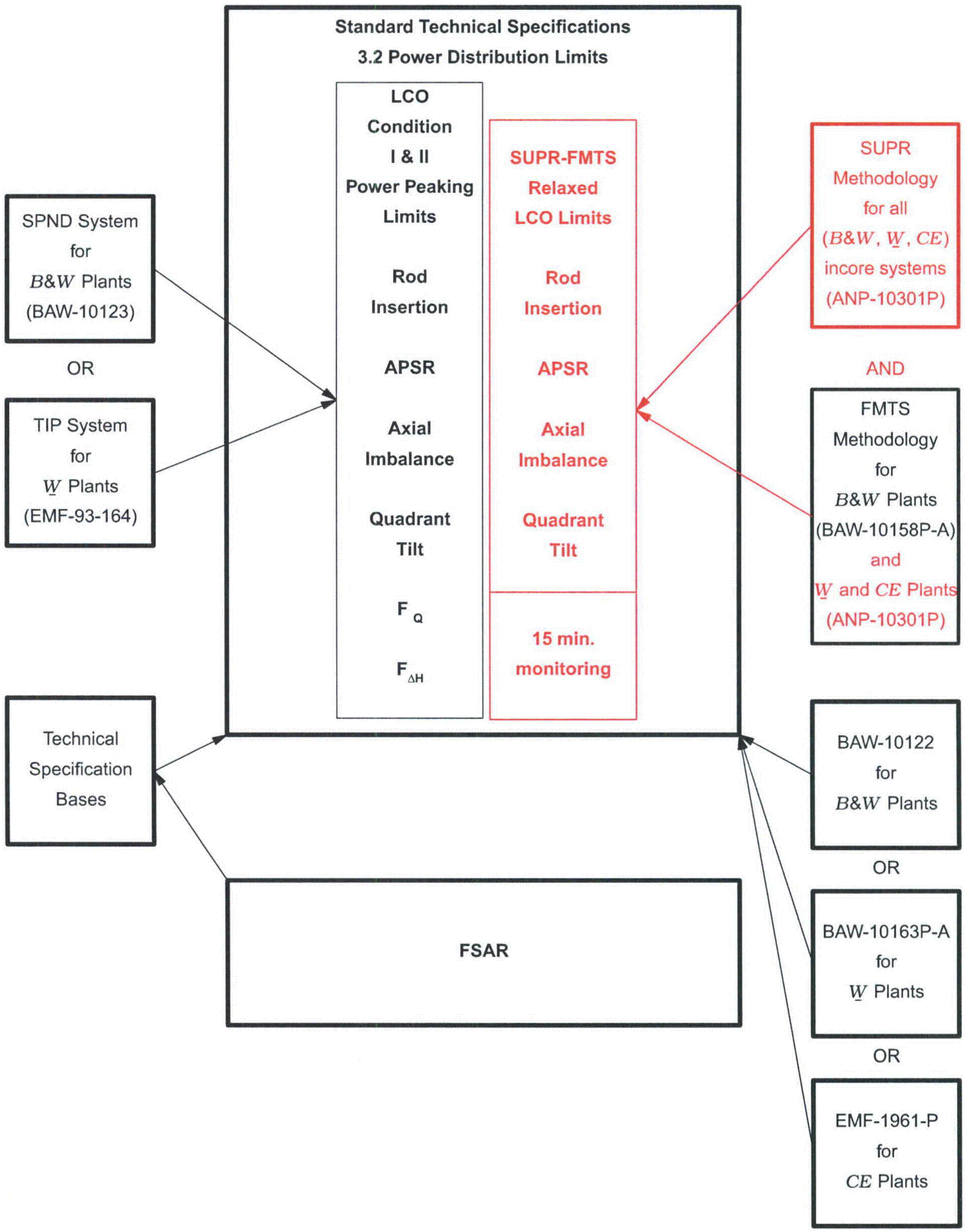
Therefore, the only changes to the Technical Specifications required to implement SUPR-FMTS are the notation of the availability of the Relaxed Limits and modification of the surveillance requirements to increase the power peaking monitoring frequency when SUPR-FMTS is operable. The adjusted kriging process variance (ADJKPV) is used to indicate inoperability of the SUPR-FMTS system.

1.4 *Approvals Requested for SUPR-FMTS*

The NRC is requested to approve the following five items:

1. Application of the FMTS methodology to Westinghouse ($\underline{W}$), EPR, and Combustion Engineering (CE) plants, as well as the previously approved Babcock and Wilcox ($B\&W$) plants [6]. This extension is based on the previous approval for Babcock and Wilcox plants, the improvement in both directness and frequency of power distribution monitoring, and the improved quantification of measurement system uncertainty through the use of the Monte Carlo simulation methodology for determining system uncertainty.
2. Application of the SUPR methodology to Babcock and Wilcox, Westinghouse, EPR, and Combustion Engineering plants for provision of measured power

Figure 1-1 Diagram of SUPR-FMTS Impacts on Technical Specifications



distributions for the required power distribution monitoring and which are based on multiple measurement systems. This is based on the improvement in both frequency and detail of the measured core power distribution from the SUPR-FMTS methodology.

3. Application of the RPD Check methodology to Westinghouse plants which use the Traveling Incore Probe system to infrequently measure the core power distribution for the required power distribution monitoring. The RPD Check method compare measured and predicted signal and augments the uncertainty applied to the SUPR measured power distribution for core power distribution Technical Specification monitoring. This is based on the continuous checking performed by the RPD Check methodology, its conservative application of only peaking increases, and the self-indication of the time when a new core flux map is required.

4. Use of the SUPR-FMTS methods justifies, under cetain conditions, extending flux map intervals beyond the approximately 31 Effective Full Power Days (EFPD) specified in current Technical Specifications.

5. Use of a Monte Carlo simulation to quantify the total system uncertainty.

1.5 *Overview of the Report*

The Technical Specifications being monitored are discussed in Chapter 2. Chapter 3 discusses the varied measurement systems that serve as the SUPR-FMTS inputs. Statistical models used to combine measurements are discussed in Chapter 4, which also covers the variance calculation and use of confirmatory data. Technical Specification monitoring requires tracking the varied sources of uncertainty, and Chapter 5 discusses the modeled uncertainty sources. In Chapter 6, a Monte Carlo simulator is used to explore the effects of the uncertainties from Chapter 5. Finally, Chapter 7 provides the method of calculation for relevant Tech Spec factors. Appendices A through D provide supporting information. The supporting information includes an illustration of the kriging and variance calculation procedure, suggested Technical Specification modifications to implement SUPR-FMTS, an operating example of the SUPR-FMTS system, and an illustration of the associated uncertainty analysis.

2.0 TECHNICAL SPECIFICATION MONITORING

The core power distribution monitoring performed by SUPR-FMTS has the following functions.

1. Monitor margins to the accident initial condition power distribution limits to provide assurance of fuel integrity during Condition I (Normal Operation) and II (Incidents of Moderate Frequency) events by (a) maintaining the calculated Departure from Nucleate Boiling Ratio (DNBR) in the core in short term transients, and (b) limiting the peak linear power density during Condition I events to provide assurance that the initial conditions assumed for the Loss of Coolant Accident (LOCA) analyses are met and the Emergency Core Cooling System (ECCS) final acceptance criteria limit of 2200°F is not exceeded.

2. Provide assurance that the core meets the local (F_Q) and integral peak ($F_{\Delta H}$) monitoring requirements.

These functions are used to satisfy the Technical Specification requirements on power distribution.

A block diagram of the relationship of these functions within the SUPR-FMTS is shown in Figure 2-1. The online core simulator produces a power distribution based on the measured plant parameters, including control rod position, axial power shaping rod position, power level, and core inlet temperature. The calculated power distribution and the available power distribution measurements are used by the kriging module to provide an estimate of the measured power distribution along with an estimate of the variance of that distribution. Where the power distribution measurements are made by infrequent systems, such as Traveling Incore Probes (TIP) or Aeroball systems, the RPD Check module is used to augment the calculated variance based on the differences between the thermocouple and excore flux detector measurements and similar values derived from the measured (reconstructed) power distribution. The adjusted Relative Power Distribution (RPD) from the Kriging module and the adjusted kriging process variance from the RPD Check module are then used in the FMTS module to monitor peaking margins to the local and planar peaking limits. Also, for a TIP system, the periodic power peaking surveillance is performed using the reconstructed power distribution and augmented variance data.

[

]

2.1 *Limiting Conditions for Operation Monitoring*

Currently, the power-distribution-related LCO limits and setpoints are based on global measured parameters such as axial flux difference (AFD), axial power imbalance, or axial shape index and quadrant power tilt, or parameters that affect the power distribution such as regulating control rod position. The SUPR-FMTS system will provide a power distribution to be used for monitoring, in real time, the proximity to the power-distribution limits, which are commonly referred to as LOCA kW/ft or nuclear heat flux hot channel factor (F_Q) limits and Initial Condition - Departure from Nucleate Boiling (IC-DNB) or nuclear enthalpy rise hot channel factor ($F_{\Delta H}$) peaking limits. The approach used for the SUPR-FMTS system is the one adopted from the AREVA NP *Fixed Margin Technical Specifications* topical report previously approved by the Nuclear Regulatory Commission (NRC) [6]. The details of the margin to peaking limit calculation are provided in Section 7.1.

When the SUPR-FMTS system is unavailable, the LCO Tech Spec limits, which are derived using currently approved methods on axial power shape, quadrant power tilt, rod position, etc. will be used as a backup until the SUPR-FMTS system is available again.

Figure 2-1 Block Diagram of Tech Spec Monitoring Functions in SUPR-FMTS

[ ]

2.2 *Provide Assurance that the Core is Operating as Designed*

The relevant core operating limits and RPD trip setpoints that preserve the LCO and the Limiting Safety System Settings (LSSS) Technical Specification power distribution limits are based on the power distributions predicted by the core design analysis models before operation of the cycle has begun. A periodic comparison of the measured power distribution is made to the nominal design values from the reload licensing analysis to provide a reasonable assurance that the core is operating within the design limits and that the power peaking limits will not be exceeded. The power distribution from the SUPR-FMTS system will be used for that purpose, as described in Section 7.3.

2.3 *Technical Specifications*

SUPR-FMTS is intended for use in multiple types of Pressurized Water Reactor (PWRs) which likely have unique Technical Specifications. Thus a fixed set of Tech Spec changes is unlikely to apply unilaterally. To accommodate this, a general discussion of the changes to Technical Specifications required to implement the SUPR-FMTS system is provided in Appendix B. The specific changes required to implement SUPR-FMTS at a given unit would be determined by a plant-specific task.

3.0 POWER DISTRIBUTION MEASUREMENT INSTRUMENTATION

The measurement of the power distribution uses several systems and methods. The local power can be calculated based on a flux measurement using a TIP, FIC detector, Aeroballs, and/or some other three-dimensional core power distribution measurement system. When necessary, the total assembly power can be calculated from assembly exit thermocouples (TCs) and the axial power shape can be indicated by an excore neutron detector (ExC) measurement. These data are used to construct the measured power distribution with varying detail and accuracy, as described in Chapter 4. Each of these systems is briefly described below, including the amount and detail of the data and the frequency of measurement, which are important aspects of these systems.

3.1 *Measurement System Categorization*

The various types of instrumentation systems can be categorized by the following attributes:

- frequency
- density
- directness

Frequency refers to the time period between successive measurements. The context here is that of measuring the power distribution to confirm operation as designed and LCO monitoring. FIC systems can measure a three-dimensional power distribution more frequently than once a minute. TIP systems have a frequency of once every one to six months.

Density refers to the spatial density of the measured data. High spatial density provides better fractional coverage of the reactor core and is therefore more likely to detect any deviation from the designed operation. TIP systems, with as much as 30% of the assemblies being measured with high axial detail, represent the highest density systems presently in use. Excore detectors and thermocouples are spatially limited and represent the other end of the density spectrum.

Directness refers to the number and accuracy of the steps used to process the measured signals. The nuclear instrumentation, including FIC, TIP, Aeroball, and excore neutron detectors, are the most direct systems. An online core simulator is less direct since it calculates the local fission rate from information about the core configuration, materials, depletion history, and global measured parameters such as power level and rod positions.

Based on this categorization of the various power distribution measurement systems each system will have strengths and weaknesses. A discussion of each of the currently utilized systems, along with a possible future concept, is provided below. A graphical depiction of the relation of these systems with respect to the density and frequency of the data is presented in Figure 3-1. Note that all of the specific points shown in Figure 3-1 can vary significantly between plant types. The figure is only intended to illustrate the differences between system.

3.1.1 *Traveling Incore Probes*

The Traveling Incore Probe system uses movable flux detectors that measure the axial and radial flux distribution in a subset of the core fuel assemblies, typically every ~31 EFPD. Typical systems cover 61 axial locations in about 30% of the radial locations within the core. The three-dimensional power distribution is extrapolated to the uninstrumented locations. This provides a relatively dense, relatively direct measurement of the core power distribution at a low frequency.

3.1.2 *Fixed In-Core Detectors*

Self-Powered Neutron Detector systems utilize fixed flux detectors that measure a detailed flux distribution in a subset of the core fuel assembly locations. Typical systems cover between four and seven axial locations in 8 to 52 radial locations within the core. The three-dimensional measured power distribution is constructed from these measurements. The spatial density varies with plant type, but the measurement is relatively direct at a high frequency, typically from one to six minutes.

3.1.3 *Aeroballs*

The Aeroball system uses Vanadium steel balls that can be placed quickly into the active fuel region of the core where they are activated for a short period of time before being removed for measurement. This provides a system that is similar to TIP systems in density and directness, but with a potentially greater frequency of measurement, typically every 15 days. The system is capable of completing a flux map every ~30 minutes if necessary.

3.1.4 *Excore Neutron Detectors*

Excore neutron detectors are generally un-compensated ion chambers placed outside the reactor vessel, two or more axial detectors for each quadrant. Their functions include monitoring the imbalance of power between the upper and lower halves of the core, monitoring total core power, and monitoring quadrant power variation (tilt) as an input to the reactor protection system. They provide a very high frequency measurements, typically every few milliseconds, to monitor fast neutron leakage from each quadrant of the core. These systems have a very low data density because the detectors are far removed from the fuel. This physical separation prevents a direct correlation of the excore current to the power distribution in specific assemblies.

Only the power range excore neutron detectors are considered for use in the SUPR-FMTS system.

3.1.5 *Fuel Assembly Exit Thermocouples*

Fuel assembly exit thermocouples measure the reactor coolant temperature at some distance above the active fuel in particular assembly locations. This measured temperature can be used to calculate the integrated power in the fuel assembly. However, assembly-exit temperature is an integral measurement, thus the axial power shape cannot be inferred from the measurement and any corrections based on the measurement must be made on an assembly, not nodal, basis. While upwards of 30% of assemblies may be monitored with a thermocouple, they are a less dense measurement because they provide no information about the axial power shape. They are less direct as well because power is inferred from a temperature difference along the assembly length and inlet flow.

3.1.6 *Future Measurement Systems*

It is conceivable that future instrumentation systems will be developed and implemented to improve the data density, directness, and/or frequency achievable by the systems. The information from these types of measurement systems can easily be incorporated to provide future improvements in core power distribution monitoring using the SUPR-FMTS methodology. The reconstruction methods discussed in Chapter 4 require only a volumetric measure of relative power to accommodate any expected future systems.

3.1.7 *Online Core Simulator*

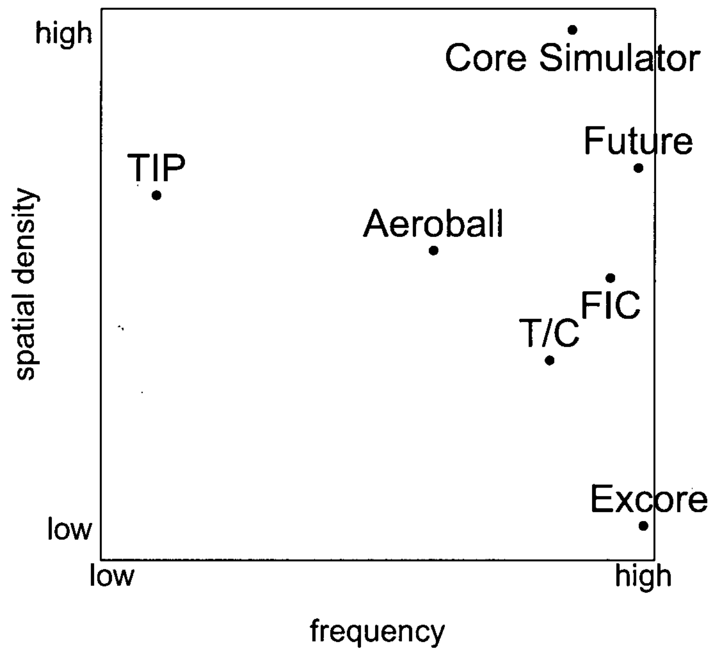
The online core simulator uses the same calculational model that was used in the pre-operational licensing analysis to establish the power distribution related limits and set-points. During operation, this model is run with input that reflects the measured power level, core inlet temperatures, and fission product distribution. This system provides a high data density at a high frequency. Since it calculates the local fission rate from assumptions regarding core configuration and global measured parameters, such as power level and rod position, it is a more indirect indication of the core power distribution. Therefore, the results of the online simulator must be periodically confirmed.

While the online core simulator output is a calculation, it does represent a number of measured global parameters and actual operating history. It is included as a measurement system to differentiate between the online simulator and the licensing analysis and to compare the output to the more traditional measurement systems.

3.2 *Statistical Universal Power Reconstruction General Approach*

The Statistical Universal Power Reconstruction approach utilizes all applicable information on the core power distribution. The system with the highest data density and frequency, the online core simulator, is used as the basis for the power distribution measurement. More direct measurement systems with high data density, such as TIP, FIC,

Figure 3-1 Categorization of Measurement Systems



or Aeroball systems, are used to make adjustments to the power distribution provided by the online core simulator. These adjustments are made using a power reconstruction method, such as the kriging models discussed in Chapter 4. The resulting measured reactor power distribution values are denoted $\hat{y}$. Alternatively, $\hat{y}$ is called the reconstructed power, which is considered to be the best available approximation of measurement.

For cores that do not use sufficiently high frequency measurement systems, SUPR-FMTS also has the capability to use indirect measurements to check the accuracy of the measured RPD. Indirect measurements, such as excore neutron detectors and assembly exit thermocouples, can provide frequent measurements, but may have higher uncertainties or provide only limited data. While these instruments might not be usable to accurately and directly measure the core power distribution, they can be used to "check" that the core continues to operate within the expected range of power distributions. This process is described in Section 4.3.

The utility of these checking routines will depend on the monitoring instrumentation available. If a sufficient number of nearly continuous measurements (e.g. FIC detectors) are available, then the checking routines are not needed. However, for plants with only infrequent measurement facilities (e.g. TIP systems in PWRs) these routines could supplement the requirements of Technical Specification power distribution surveillance requirements.

To provide a useful check, the higher uncertainties of these sparse-density, frequent-measurement systems are reflected in the calculation uncertainty so that the reconstructed power is not at risk of reflecting potentially poor quality data. Any uncertainty will be accounted for in the margin calculation and is discussed in detail in Section 4.3.5 and Section 7.1.

3.3 *SUPR-FMTS Processing Overview*

To clarify the function of the SUPR-FMTS system, this section shows a generalized example calculation. Details of the methodology, including variable definitions and explanation, are found in Chapter 4 and a detailed example calculation is given in Appendix A.

The reconstructed nodal RPD is calculated as:

$$\hat{y}(\mathbf{x}_0) = g(\mathbf{x}_0) + \mathbf{r}(\mathbf{x}_0)^{\mathrm{T}}\mathbf{R}^{-1}(\mathbf{y} - \mathbf{g})$$

This equation is composed of three basic quantities: $\hat{y}(\mathbf{x}_0)$ is the reconstructed power at node $\mathbf{x}_0$, $g(\mathbf{x}_0)$ is the most recent result for the core neutronic simulator at node $\mathbf{x}_0$, and **[**

] The final term is calculated with each new measurement and adjusts the neutronic simulator output to agree with measurements.

The variance is then calculated as: **[**

]

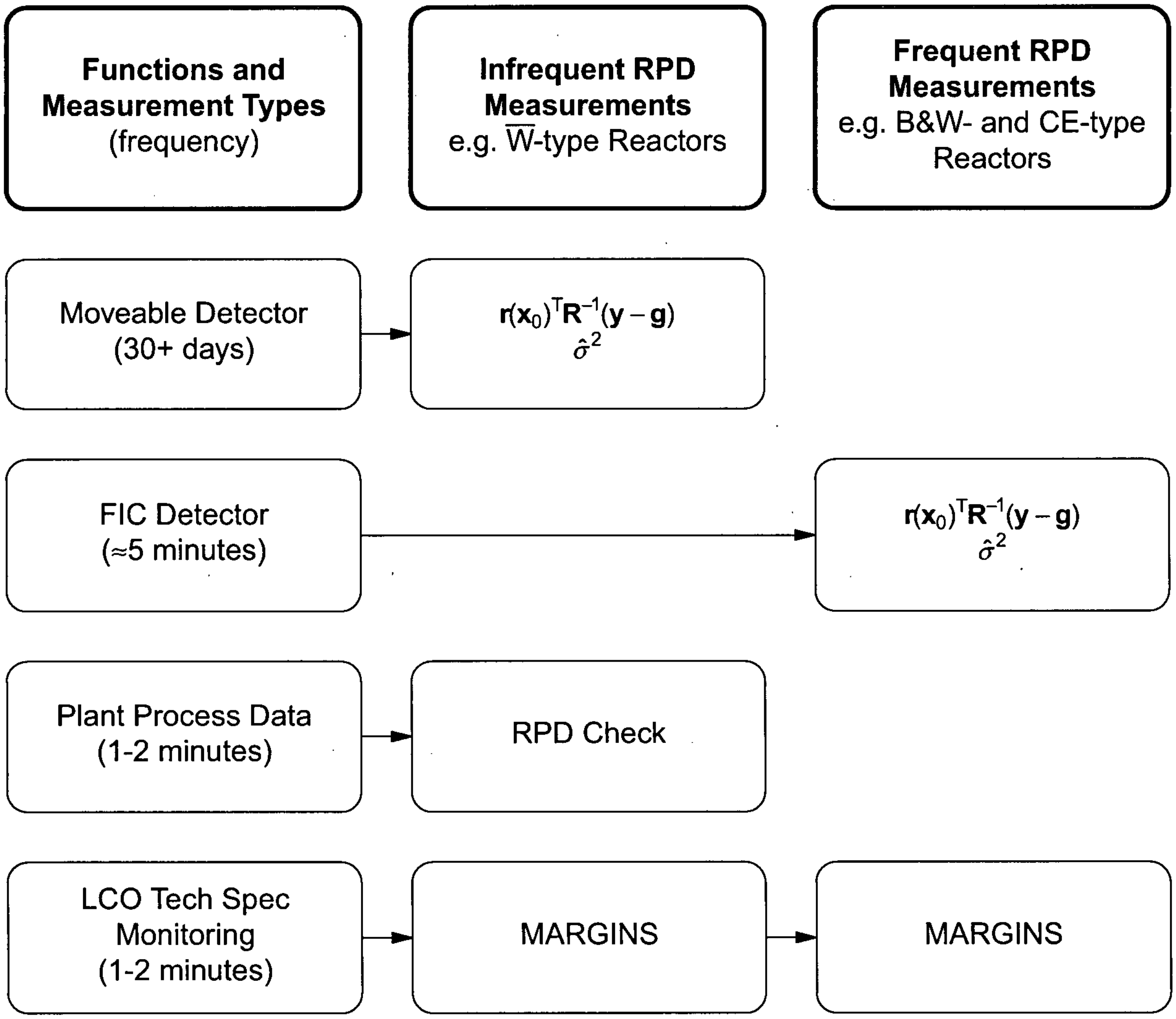
Where necessary—typically in reactors without fixed incore detectors—the RPD checking routines are used. These routines produce expected values for frequently measured parameters, such as assembly exit thermocouple and excore neutron detector measurements, and compare the expected values to those measured. If the expected and measured values differ by more than [ ], an augmentation factor is applied to the variance. The new, increased, variance is chosen such that [ ]

This augmented variance is incorporated into the total uncertainty applied to the LCO peaking margin calculations, as shown in Chapter 7. The augmentation accounts for the uncertainty due to differences between calculated and measured values as well as the uncertainty introduced via spatial interpolation.

Figure 3-2 shows when the above equations are calculated and gives an idea of typical frequencies. The types of PWRs are shown to illustrate the different SUPR-FMTS processing required with and without frequent RPD measurement systems. The actions in the left column (measurements) will trigger the calculations shown in the other two columns, depending on the plant type.

For all of the actions shown in Figure 3-2 the core neutronic simulator is assumed to provide a current calculation **g**.

Figure 3-2 SUPR-FMTS Processing and Timing Overview



4.0 CORE POWER DISTRIBUTION MEASUREMENT

The SUPR-FMTS measured power distribution is the output of an online core simulator [7, 8] adjusted to match the available measured data. This approach is taken to capitalize on the highly detailed core simulator output by bias-correcting it to match the sparser but accurate measurement data. That is, the core simulator output is adjusted to produce a more detailed measured or reconstructed reactor power distribution that is the most consistent with the reference measurements.

Some set of measured data are used to find the bias of the core simulator output in discrete volumes (nodes) of the reactor. These biases (residuals) are then interpolated using [ ] to produce the reconstructed power distribution in uninstrumented locations. The concept [ ] is discussed in Section 4.1. Kriging is a statistical process used for spatial and temporal interpolation which has been adapted from the field of geostatistics for this application, as discussed in Section 4.2.

In some cases, a "check" of the Best Estimate Relative Power Density (BE RPD, $\hat{y}$) is necessary to ensure validity of the reconstructed power distribution between measurements. If such a check is necessary, as discussed in Section 3.2, then the RPD checking routines discussed in Section 4.3 are used.

4.1 *The Model Illustrated*

Each measured RPD is calculated [ ] For example, a 177 Fuel Assembly (FA) plant modeled in 18 axial levels [ ] While this may be computationally demanding, it allows [ ] which is considered to be more consistent with reactor physics behavior, [ ] Any global bias is mitigated by the relative nature of the RPD and is revealed through the RPD Check routines discussed in Section 4.3.

[ ]

[ ]

Figure 4-1 Two Models Used for Calculating the Relative Power Density

[ ]

4.2 *The Kriging Model*

Kriging is a method to calculate the best unbiased linear estimator of an unknown field by using a stochastic model of the spatial variance of the field. It was initially formalized in the field of geostatistics, but has since been adapted to other fields, such as meteorology, as an optimal interpolation technique. Kriging provides a method that minimizes the variance of the prediction error, where the interpolation variance is quantified in a relative form.

4.2.1 *Interpolation with Kriging Models*

The goal of kriging is to find an estimate of an unknown field $y(\mathbf{x})$, the relative power in this case, at a point $\mathbf{x}_0$ (boldface indicates a vector or matrix), given the value of this field at a series of N points: $y(\mathbf{x}_1), y(\mathbf{x}_2), ..., y(\mathbf{x}_N)$. For a single kriging model, $\mathbf{x}_0$ would be a scalar but multiple kriging models are used to make the reconstructed power distribution. Since a series of $\mathbf{x}_0$ (and similar) values are needed to form $\hat{y}$, the vector notation is used. The statistical model used to develop this estimate is [9]

$$y(\mathbf{x}) = g(\mathbf{x}) + \varepsilon(\mathbf{x})$$

where

$g(\mathbf{x})$ is the trend model

$\varepsilon(\mathbf{x})$ is the error, a random deviation from the trend

The choice of trend model determines the type of kriging. For this application, the trend model is the output of the core simulator, which is known. Thus, there are no parameters in the trend model to estimate when performing the interpolation (not even the mean value of the trend, since the mean relative power density is one by definition).

The stochastic model used for the errors assumes that they are correlated and stationary—i.e., the covariance between two measurements depends only on the relative vector $\mathbf{h}$ (in space and time) between the two. Thus, the covariance of the residual field can be written as a function of only one vector parameter:

$$\mathrm{Cov}[\varepsilon(\mathbf{x}), \varepsilon(\mathbf{x}+\mathbf{h})] = c(\mathbf{h})$$

which is valid for all **x**. The residual field is the distribution of error over **x**.

With the stochastic model of the spatial dependence quantified by the covariance, the kriging estimator at $\mathbf{x}_0$ is a linear combination of the measured values:

$$\hat{y}(\mathbf{x}_0) = \sum_{i=1}^{N} w_i \, y(\mathbf{x}_i)$$

where the weighting factors w_i are chosen to minimize the variance of the difference between the estimated value and the real value, which is called the *kriging variance:*

$$\sigma_{\mathrm{K}}^2(\mathbf{x}_0) = \mathrm{Var}\left[\hat{y}(\mathbf{x}_0) - y(\mathbf{x}_0)\right] \quad (4\text{-}1)$$

which can be written [9]

$$\sigma_{\mathrm{K}}^2(\mathbf{x}_0) = \mathbf{w}^{\mathrm{T}}\mathbf{C}\,\mathbf{w} + \mathrm{Var}\left[y(\mathbf{x}_0)\right] - 2\,\mathbf{c}_0^{\mathrm{T}}\,\mathbf{w}$$

where

w is the vector of weighting factors

C is the matrix of covariances between the measured data, $C_{ij} = c(\mathbf{x}_i - \mathbf{x}_j)$

$\mathbf{c}_0$ is the vector of covariances between $\mathbf{x}_0$ and the location of each measured point, $[\mathbf{c}_0]_i = c(\mathbf{x}_0 - \mathbf{x}_i)$

Note that k (no italics) denotes "kriging" while k (in italics) denotes an indexed value.

In addition, kriging assumes that the estimated value is unbiased

$$\mathrm{E}\left[\hat{y}(\mathbf{x}_0)\right] = \mathrm{E}\left[y(\mathbf{x}_0)\right]$$

where E[x] denotes the expected value of the random quantity x. In this case, however, y is the RPD, a relative quantity. Thus, its mean is known

$$\mathrm{E}\left[\hat{y}(\mathbf{x}_0)\right] = \mathrm{E}\left[y(\mathbf{x}_0)\right] = 1$$

and the unbiased condition is satisfied without requiring an additional constraint.

With this set of assumptions, the kriging predictor can be written

$$\hat{y}(\mathbf{x}_0) = g(\mathbf{x}_0) + \mathbf{c}_0^{\mathsf{T}}\mathbf{C}^{-1}(\mathbf{y} - \mathbf{g}) \tag{4-2}$$

where

> **y** is the vector of measured points, $y_i \equiv y(\mathbf{x}_i)$
>
> **g** is the vector containing the core simulator output at each of these locations, $g_i \equiv g(\mathbf{x}_i)$

Thus, $(\mathbf{y} - \mathbf{g})$ is the vector of residuals, which provide an estimate of the error.

[

] where σ^2 is the variance of the error ε and the covariance parameters θ_k give a measure of the influence that a particular point has on its neighbors. For example, along the k-th direction, the covariance of residuals at a distance greater than [ ] is less than [ ] of the field's variance; thus, the influence of these residuals on the estimated value can be considered negligible. [

] If the covariance parameters are all similar in value, this region [

] For the implementation described here, the domain of the model [

] That is, only [

]

It is possible to verify both the assumption of a [ ] form for the covariance function and the values of the parameters θ_i with a leave-one-out cross-validation. In particular, statistical software (in this case, packages for the R statistical programming language) allows the user of this technique to check different parameters, differently sized domains, and even a different functional form for the covariance to ensure that the average error is sufficiently small.

The variance of the error, σ^2, which is still unknown, appears only in $\mathbf{c}_0$ and $\mathbf{C}$ in Eq. (4-2). Thus, the kriging predictor is independent of this value, since these terms cancel in $\mathbf{c}_0^T\mathbf{C}^{-1}$. This can be made explicit by introducing a correlation function that retains only the exponential part of the covariance function between two vectors **a** and **b**: **[**

]

The k indices are typically the three spatial dimensions, i, j, k, but any dimension, e.g. time, can be valid if the covariance function is applicable. This function can be used to define a vector that relates the location of the estimator, $\mathbf{x}_0$, and the locations of the measured data, $\mathbf{x}_1, ..., \mathbf{x}_N$:

$$\mathbf{r}(\mathbf{x}_0) = \begin{bmatrix} R(\mathbf{x}_0, \mathbf{x}_1) \\ \vdots \\ R(\mathbf{x}_0, \mathbf{x}_N) \end{bmatrix}$$

and a matrix that correlates the locations of the measured data to each other:

$$\mathbf{R} = \begin{bmatrix} R(\mathbf{x}_1, \mathbf{x}_1) & \cdots & R(\mathbf{x}_N, \mathbf{x}_1) \\ \vdots & & \vdots \\ R(\mathbf{x}_1, \mathbf{x}_N) & \cdots & R(\mathbf{x}_N, \mathbf{x}_N) \end{bmatrix}$$

The vector $\mathbf{r}(\mathbf{x}_0)$ explicitly depends on the location $\mathbf{x}_0$ of the estimate, and thus, this dependence is indicated in the notation. The matrix $\mathbf{R}$, on the other hand, has no explicit dependence on $\mathbf{x}_0$; however, it should be noted that the set of measured points that are used to construct $\mathbf{R}$ depend on the location $\mathbf{x}_0$, since only the points in the domain of the model $D(\mathbf{x}_0)$ are included in the set.

[

]

The kriging predictor can be rewritten using this new correlation vector and matrix as

$$\hat{y}(\mathbf{x}_0) = g(\mathbf{x}_0) + \mathbf{r}(\mathbf{x}_0)^T \mathbf{R}^{-1}(\mathbf{y} - \mathbf{g})$$

4.2.2 *Notation for the Core Simulator*

For the particular application considered here, the trend function is the output of the core simulator, which provides the core power on a regularly spaced arrangement of nodes. Therefore, each location in the model can be represented by the indices of the node's location in the simulator and the time. The following sets of indices are used in the notation presented here:

(i, j, k, t) indicates a location $\mathbf{x}_0$

(i, j, k) indicates a location $\mathbf{x}_0$ that does not include the time of the measurement or calculation

(i, j) indicates the two-dimensional (horizontal) location of an assembly in the core

This notation is also applied to the reconstructed power, $\hat{y}$, and the kriging process variance, $\hat{\sigma}^2$.

4.2.3 *Kriging Variance Calculation*

As discussed in Section 4.2.1, kriging provides the unbiased estimate that minimizes the kriging variance, which is given in Eq. (4-1). In terms of the correlation vector $\mathbf{r}(\mathbf{x}_0)$ and matrix $\mathbf{R}$, this variance can be written [10]

$$\sigma_k^2(\mathbf{x}_0) = \sigma^2\left(1 - \mathbf{r}(\mathbf{x}_0)^T \mathbf{R}^{-1} \mathbf{r}(\mathbf{x}_0)\right)$$

As the location $\mathbf{x}_0$ of the interpolated value moves away from the measured data, the uncertainty approaches its maximum value σ^2, which is called the *process variance.* Thus, σ^2 represents an upper bound on the uncertainty of the [ ] model.

The process variance includes variance due to error (residuals between calculation and measurement) as well as the variance due to kriging (interpolation). The SUPR-FMTS method relies on quantifying the uncertainty due to both sources, so the process variance is used.

[ ] is used to provide an objective estimate of the process variance. If the error in the trend (core neutronic simulator output) is [ ] then the series of residuals from the measurements used for the model, $(\mathbf{y}-\mathbf{g})$, [ ] Thus the likelihood of the process variance σ^2 is equal to [

]

This estimate is used by the system to calculate the process variance [
]

Because the errors are assumed to be normally distributed, the 95% confidence interval for each node in the model is

$$95\%\ CI(i,j,k) = \left[\hat{y}(i,j,k) - 1.96\ \hat{\sigma}(i,j,k),\ \hat{y}(i,j,k) + 1.96\ \hat{\sigma}(i,j,k)\right]$$

4.2.4 *Temporal Dependence of the Kriging Model*

Although the formalism for the method developed in this section contains a temporal component, the frequency of measurement determines whether the elapsed time since the measurement is significant enough to include in the interpolating scheme in practice. That is, for systems that provide nearly continuous measurements, such as fixed incore detectors, the time between measurements, Δt is sufficiently short that **[**

]

for a choice of θ_t that is large enough to be used for less frequent (but more accurate) measurement systems. Thus, for these nearly continuous systems, the temporal dependence is dropped from $R(\mathbf{a}, \mathbf{b})$, and the components of **r** and **R** may have either three or four terms depending on the source of the measured data.

The use of nearly continuous measurement systems has other consequences for the monitoring system, as well. These consequences are discussed in further detail in Section 3.2.

4.3 *Checking the RPD and Uncertainty*

The monitoring system includes a checking routine that takes the output RPD from the kriging module ($\hat{y}$), generates expected responses, and compares the expected responses to measured responses. If the comparison of the two sets of values indicates that the kriging variance is not sufficiently conservative, the variance is adjusted to match the observations.

4.3.1 *Converting the Best Estimate RPD to an Expected Response*

The expected responses are compared with the measured responses to gauge whether the kriging uncertainty needs to be adjusted to properly reflect the Observed Reactor Behavior (ORB). In the current implementation, the responses from only two devices are considered: the assembly exit thermocouples and the excore neutron detectors.

The calculation of the response of these two devices is described below. For other systems, such as a sparse FIC system, the checking would be done [
]

4.3.1.1 *Calculating the Thermocouple Response*

The expected temperature of each thermocouple is calculated using an energy balance over the length of the fuel assembly:

$$T_{out} = \frac{Q(i, j)}{\dot{m} C_p} + T_{in}$$

where

T_{out} is the exit temperature
$Q(i, j)$ is the rate of heat generation by the assembly
$\dot{m}$ is the coolant mass flow rate
C_p is the specific heat of the coolant
T_{in} is the inlet temperature

The assembly power $Q(i, j)$ is found using $\hat{y}(i, j, k)$, which has been collapsed to two dimensions, and the nominal assembly power. Nominal assembly power, $\bar{Q}(i, j)$ is calculated by dividing the core thermal power by the number of assemblies in the core.

$$Q(i, j) = \hat{y}(i, j) \cdot \bar{Q}(i, j)$$

[ ] the specific heat capacity of the coolant, C_p, is estimated at the average of the mean cold-leg and mean thermocouple temperatures. [

] Assembly inlet temperatures are estimated from the measured cold-leg temperatures and plant-specific information.

4.3.1.2 *Mass Flow Rate Calibration and Interpolation*

Whenever a detailed flux measurement (e.g., using the TIP) is performed, a new set of calibrated assembly mass flow rates is calculated using the current set of thermocouple temperatures. There are two important ramifications of this procedure: (1) a detailed flux measurement must be taken before thermocouple data can be used as ORB, and (2) there will be no difference between the expected and measured thermocouple responses immediately after calibration.

The mass flow rates are calculated assuming an enthalpy balance at the calibration time. No appreciable temperature increase between the cold leg measurement point and the assembly inlet is assumed. Assembly inlet temperature calculations are taken from the core monitoring software.

The enthalpy balance for a fuel channel is

$$h_{outlet} - h_{inlet} = \frac{1}{\dot{m}} \int_{inlet}^{outlet} q'(z)\, dz$$

where

h_{outlet} is the coolant enthalpy at the thermocouple location
h_{inlet} is the coolant enthalpy at the assembly inlet
$\dot{m}$ is the mass flow rate
$q'(z)$ is the linear rate of heat generation

The integral in the expression above is the total power generated in the assembly. Solving for the mass flow rate in an individual assembly yields

$$\dot{m}(i,j) = \frac{\hat{y}(i,j) \cdot \bar{Q}(i,j)}{h_{outlet}(i,j) - h_{inlet}(i,j)}$$

[

]

The SUPR-FMTS is flexible enough to include partial flux measurements as well, simply by augmenting the integrated TIP measurements from the partial scan with TIP data from previous scans. However, using old TIP data would indicate that the user is confident in the calibration values in the neighborhood of those measurements.

4.3.2 *ExCore Detector Responses*

This method requires the addition of the axial weighting factors for the top and bottom detectors, which are described below:

$\omega_{i,j}^{adj}$ – calculated assembly weights

$\omega_{k}^{adj\_U}$ – excore detector response weights (upper axial direction)

$\omega_{k}^{adj\_L}$ – excore detector response weights (lower axial direction)

A three-dimensional weighting factor matrix can be constructed for each detector. The four upper-quadrant and four lower-quadrant weights are identical, so only two unique matrices are required:

$$\phi_{i,j,k}^{U} = \omega_{i,j}^{adj} \cdot \omega_{k}^{adj\_U}$$

$$\phi_{i,j,k}^{L} = \omega_{i,j}^{adj} \cdot \omega_{k}^{adj\_L}$$

These arrays are pre-calculated and stored as a data file that contains both sets of adjoint weighting factors.

To find the calculated or expected detector response, the weights are multiplied by the RPD from the core simulator. Since the weights cover only one-quarter of the core (or a quadrant), each weighting matrix is multiplied by each of the four quadrants to get a total of eight detector responses:

$$\gamma^{ExCore,U}(q) = \sum_{i,j,k} \phi_{i,j,k}^{U} \cdot \hat{y}(i,j,k)$$

$$\gamma^{ExCore,L}(q) = \sum_{i,j,k} \phi_{i,j,k}^{L} \cdot \hat{y}(i,j,k)$$

These detector responses are normalized and compared to the excore voltages from the plant process computer as described in the following section.

4.3.3 *Convert Kriging Variance to Expected Response Variance*

In order to compare responses (the purpose of the RPD check routine), the kriging variance must be transformed to a response variance. This section describes this procedure for the assembly exit thermocouples and excore neutron detectors.

4.3.3.1 *Thermocouple Response Variance Calculation*

As described in Section 4.3.1.2, the assembly exit temperature is calculated using an enthalpy balance and a calibrated mass flow rate. **[**

]

The mass flow rate, $\dot{m}$, is calibrated to detailed flux measurements, and both enthalpy terms are functions of a known temperature. Note that none of these three terms are variance-free; rather, the assumption here is that the variance of the core simulator is the primary contribution to the uncertainty. The secondary contributions will be quantified as part of the total observability error, which is discussed in Chapter 6.

The core thermal power (CTP) and number of assemblies in the core are also assumed to be known exactly. Thus, the only term left containing significant uncertainty is the two-dimensional RPD, which is an axially-averaged form of the best estimate (kriged) RPD. Denoting the kriging variance at each of the N axial levels as **[** **]** and assuming all other terms to be constant, the enthalpy balance equation reduces to:

[

] which is used in Section 4.3.4.

4.3.3.2 *ExCore Voltage Variance Calculation*

The expected excore response is calculated as described in Section 4.3.1.2. Assuming that the uncertainty of the weighting factors is a secondary effect quantified in the total observability error calculation, the standard deviation of the excore response is calculated from [

]

4.3.4 *Comparison of the Expected Response to the Measured Response*

To test the reliability of the output of the model, the expected response given by the model is compared to the response given by measurements.

[

]

[

]

4.3.5 *Adjustment of the Kriging Variance Based on the Test Results*

[

] The superscript asterisk (*) denotes a value updated during the RPD checking process. The value of [ ] then has to be [

] For the thermocouple locations, the enthalpy calculations described in Section 4.3.3.1 are reversed to find [ ] A new term is defined, the thermocouple adjustment factor, R_{TC}, that is [

] for locations that pass the test. The values in uninstrumented locations are interpolated from the neighboring measured locations.

A similar process is used to create the excore detector adjustment factor, $R_{ExC}(i, j)$. Since the excore detectors do not give sufficient detail to discern individual node effects, the adjustments are applied [ ] Any assemblies that could contribute [

]

After the comparisons to the measured values have been made, the adjustments are applied [ ]

[

]

5.0 MEASUREMENT SYSTEM UNCERTAINTIES

The SUPR-FMTS requires a number of measured parameters to construct a core power distribution. The core simulator needs the power level, inlet temperatures and rod positions. The kriging module needs the relative power values for the measured locations in the core, from each of the power distribution measurement systems that are utilized. Each of these measured values has an uncertainty that must be included in the evaluation of the total SUPR-FMTS uncertainty. In addition, the online core simulator model chosen has an uncertainty associated with it. Finally, the kriging method will estimate an uncertainty based on the data density and this will be included in the total SUPR-FMTS uncertainty. The overall flow of information and the uncertainties are depicted in Figure 5-1.

Each of these uncertainties, including their sources, is described. Since the measurement systems and their associated uncertainties vary based on the specific plant configuration, example values will be provided here for illustration. The application of this method to a specific plant configuration will include performing a SUPR-FMTS system uncertainty analysis for that plant configuration using the methods presented in this report.

The method used to determine the total SUPR-FMTS uncertainty will be described in Chapter 6.

5.1 *Measured Plant Parameters*

This type of measured parameter includes the power level, inlet temperatures and rod positions which are generally used as inputs to the core neutronic simulator. Table 5-1 shows typical uncertainty values for a Westinghouse-designed 193 fuel assembly plant.

5.2 *Power Distribution Measurement Systems*

There are several core power distribution measurement systems currently in use. Each of these systems uses detectors to measure a specific parameter and provide signals

Figure 5-1 Flow of Information and Uncertainties in the SUPR-FMTS

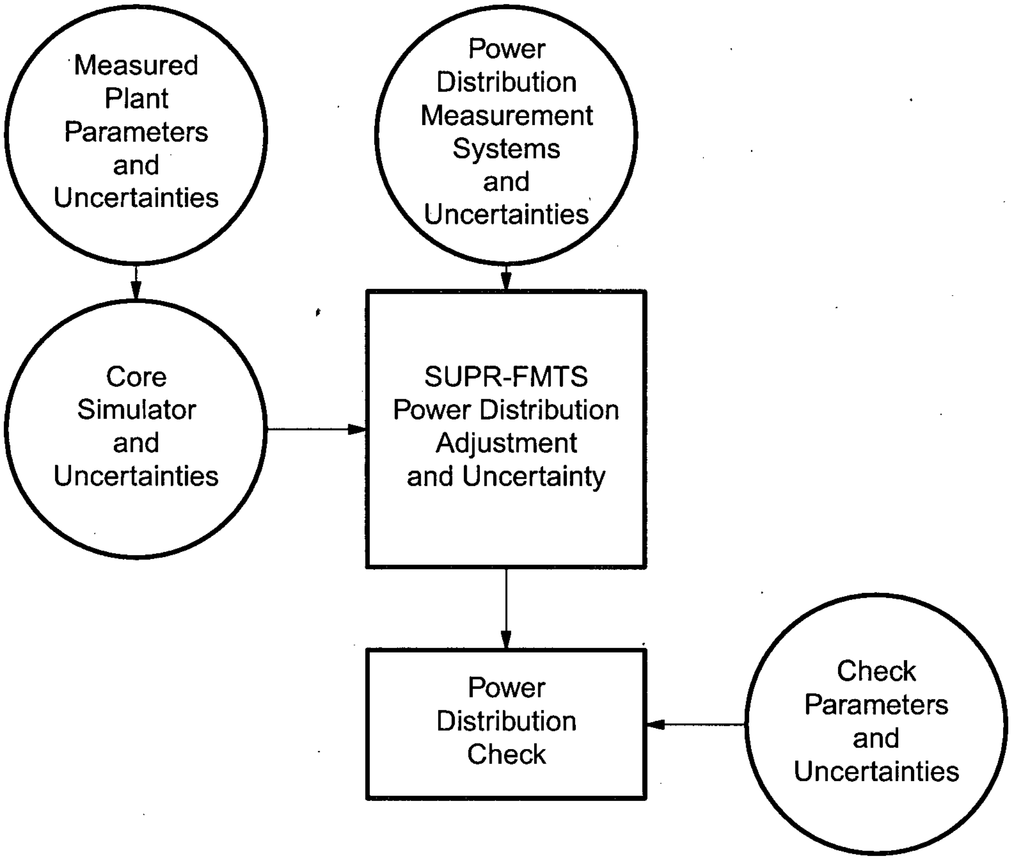


Table 5-1 Example Plant Parameters and Their Uncertainties

[ ]

which are converted to relative power in a given volume. In existing codes, these local powers are extrapolated using various methods to produce a complete three-dimensional power distribution for the core. In the SUPR-FMTS, the methods described in Chapter 4 are used to expand the local relative power measurements from one or more measurement systems to a complete three-dimensional power distribution.

The uncertainty in the instrumentation systems includes sensor uncertainty, amplifier and other electronics system uncertainty, the uncertainty of conversion of the signal to power, and any uncertainty in the measured-to-unmeasured location expansion. This uncertainty has previously been quantified and described for instrumentation that is already in use. Therefore, for a specific installation, the values will be the same as those already licensed for use and will only need to be quantified for a new type of instrumentation system. Examples of present commonly used systems are shown in Table 5-2 along with typical uncertainty values.

The uncertainty of these systems has been evaluated and applied in the licensing and operation of previous fuel cycles. This system uncertainty includes both the uncertainty for measured locations and also the uncertainty of extrapolating to the unmeasured locations. Since the SUPR-FMTS constructs its own power distribution, only the information from the instrumented locations is used from the power distribution measurement systems and therefore, only the portion of the measurement system uncertainty reflecting this measured subset of locations needs to be incorporated into the SUPR-FMTS total system uncertainty evaluation. Where the measurement system uncertainty value reflects the uncertainty in the peak and not just the instrumented locations, it will be conservative to apply the peak uncertainty if the instrumented location uncertainty is not available. As an example, for a TIP system, the uncertainty in the relative power in

Table 5-2 Typical Instrumentation Systems and Their Uncertainties

[ ]

the peak locations is typically [ ] Since this system is inter-calibrated among all instrumented locations, the uncertainty in the instrumented locations should be much less than [ ] Optionally, the [ ] value may be conservatively used in place of the actual, lower instrumented location uncertainty value.

5.3 *Online Core Simulator*

Since the online core simulator uses the same model as is used to calculate the power distribution-related LCO and LSSS limits, the uncertainty derived for the model and applied in the determination of the operating limits will also be used in the SUPR-FMTS. An example is the use of the NEMO [8] computer code. This model is used to provide the base three-dimensional power distribution that represents the expected reactor state based on the present core power level, inlet temperature and control rod positions. It also reflects the present fission product distribution. This information is used to relate the measured to the unmeasured locations. Therefore, the uncertainty in the nodal power is incorporated in the SUPR-FMTS total uncertainty evaluation. For this code, the uncertainty in the nodal power distribution is [ ]

5.4 *Check Parameters*

The high frequency but low density measured parameters, such as thermocouples and excore detectors, must be calibrated to the high density measurements at the times that they are performed, whether frequent or infrequent. Even when calibrated, the use of these parameters to infer core power distribution has a high uncertainty. This uncertainty includes the effects of several factors such as instrument drift, change in coolant temperatures, and shift in power distribution due to changes in fuel burnup, xenon distribution, and other fission products as well as large observability errors resulting from the low data density. These uncertainties are included in the analysis, as described in Chapter 6.

As discussed in Section 3.2 the check parameters are only used when sufficient, real-time instrumentation is not available, such as for the use of TIP systems.

6.0 DETERMINATION OF TOTAL SYSTEM UNCERTAINTY

This chapter describes the method used to evaluate the SUPR-FMTS total system uncertainty. This uncertainty is applied in the online calculation of the peaking margin to the LCO peaking limits (LOCA and IC-DNB). This method combines the uncertainties in the measured plant parameters, power distribution measurement systems, and the core simulator using a Monte Carlo simulator to quantify the total error of the system. Here the total error includes both the known uncertainty in measurement and calculation systems as well as the limitations of the systems for a given reactor and instrumentation configuration.

The following subsections discuss each of these uncertainty components. Section 6.1 discusses how the factors from Chapter 5 are applied as part of the total system uncertainty quantification. The range of possible limiting power distribution cases are discussed in Section 6.2. Section 6.3 and Section 6.4 outline the total uncertainty determination and application, respectively.

6.1 *Plant Parameter and Measurement System Uncertainties*

As shown in Figure 2-1, the plant parameters define an important part of the input for the online core simulator and therefore any uncertainty in these values will affect the core simulator produced RPDs. The uncertainties in the detailed measured power distribution, including the effects of failed detectors or otherwise unavailable measurements, will affect the Best Estimate RPD ($\hat{y}$ in Chapter 4). The use of this power distribution to generate frequent, sparse parameter values for such things as assembly exit thermocouples and excore flux detectors for comparison to the measured values of these parameters will produce additional uncertainty in the comparison. In the evaluation of the total system uncertainty, all of these uncertainties are applied to the SUPR-FMTS system.

6.2 *Expected Range of Limiting Power Distributions*

A range of phenomena can occur which can cause increases in the local power distribution. The total amount of the increases may be under-measured by the power distribution measurement system. These effects are called the *observability uncertainty*. The amount of under-measurement will depend on how local the power increase is and the geometric distribution of detectors. This uncertainty must be included in monitoring the core power distribution at conditions producing power peaking with a magnitude approaching the power peaking limits. The quantification of this uncertainty is performed by modeling events that would produce a significant localized power increase. The types of events examined which produce these limiting power distributions are given in Table 6-1.

This category of occurrences represents those phenomena that are either not monitored or mis-measured and have an impact on the core power distribution. More global effects will be reflected in the measured power distribution to relatively greater degrees. Therefore, the focus of this analysis is on those occurrences that are most local in their effect.

Another occurrence that increases the observability uncertainty in the power distribution measurement is the reduction in the number of measured core locations due to events such as the failure of a detector or electronics, or the plugging of a thimble tube. The

Table 6-1 Types of Events Examined

effect of these can be evaluated by including a simulated random failure of a specified fraction of the measurement locations in the system uncertainty analysis using the methods described in Section 6.3. The SUPR-FMTS system uncertainty is quantified as a function of the fraction of measurement failures and applied in the LCO monitoring. The increase in system uncertainty with increasing failure fraction is incorporated as shown in Section 7.1.4.2 and as described in Appendix D.

6.3 *Method of Determining Total Uncertainty*

The SUPR-FMTS total system uncertainty is determined through the use of a Monte Carlo simulation of the reactor core, instrumentation systems, and the SUPR-FMTS monitoring system. This is illustrated in Figure 6-1.

[

]

6.4 *Application of the Total System Uncertainty*

The total uncertainty in the measurement of the power distribution described above is directly applied to the measured power distribution to calculate the margin to the peaking limits required by the LCO Technical Specification Limits. If the margin drops below zero, an LCO alarm is generated by the computer and the operator must begin actions to bring the power peaking back within allowable initial condition limits or reduce reactor thermal power.

Figure 6-1 Monte Carlo Simulation of Reactor Core and Measurement Systems to Determine Total System Uncertainty

[ ]

7.0 TECHNICAL SPECIFICATIONS AND MONITORING METHODS

The previous chapters have described the generation of measured power distributions, the measurement systems and their uncertainties, and the evaluation of the total system uncertainty. This chapter describes the types of Technical Specifications modifications which are required to use the power distribution measured by the SUPR and monitored by the FMTS to preserve the power peaking limits which provide assurance of fuel integrity during Condition I and II events. Other Technical Specification modifications required to change the flux map interval when using TIPs are also described. The approach to modifying the Technical Specifications and changes to the Standard Technical Specifications based on this approach are provided in Appendix B.

7.1 *FMTS Requirements*

In operation, limits can be placed on plant parameters that affect the core power distribution to prevent power peaking from exceeding limits on F_Q and $F_{\Delta H}$ which in turn preserve the assumptions used in the accident analyses to provide assurance of fuel integrity during Condition I and II events. Common parameters used for LCO limits that affect power peaking include individual control rod and control rod bank positions. Additional limits can be placed on measured parameters that reflect the power peaking, such as axial power imbalance and quadrant power tilt. Both of these approaches include conservatism that is not required if the power peaking is measured directly with sufficient frequency and margin to the peaking limits is controlled. If power peaking is measured with sufficient accuracy, detail, and frequency, LCO alarms may be based on proximity to the power peaking limits. This approach was approved previously [6] for use with FIC detectors. For reactors with infrequently used power distribution measurement equipment, a core simulator is used which reflects the effects of control rod positions, fission product distribution, and coolant temperature distributions. The core simulator is adjusted by the infrequently measured power distribution and, for times between those measurements, adjustments are derived from comparison of the power distribution inferred from the online core simulator to less detailed but more frequently measured power distribution indicators such as assembly exit thermocouples and excore flux detectors.

The SUPR-FMTS produces a measured power distribution every few minutes. This methodology includes the 3-D core simulator as is presently used to determine the LCO and LSSS power distribution-based core protective limits. For example, NEMO [8] or PRISM [7] or any future approved core simulator could be used by this methodology. The core simulator is the same as the licensing model (or validated to be consistent with it) and is linked with the existing measurement system through SUPR-FMTS. Surveillance requirements confirm that peaking limits are within the established boundaries of the safety analysis of each plant. The typical limits of interest are a local peak limit commonly referred to as F_Q and a planar peaking limit commonly referred to as $F_{\Delta H}$. This comparison is made by calculating the margin to the peaking limit. Peaking margin is defined as follows for local peaking margin.

$$M_{i,j,k} = \left(1 - \frac{RPD_{i,j,k} \cdot R_{local} \cdot F_{total}}{L_{i,j,k}}\right) \cdot 100$$

where

i, j = the assembly location

k = the axial location

M = Percent margin to the limit

RPD = Relative Power Density for the i,j,k node

R_{local} = pin to assembly average power ratio

F_{total} = total uncertainty factor, see discussion in Section 7.1.4

L = Limit on relative pin power to provide assurance of fuel integrity

Similarly, the peaking margin for planar peaking limits is calculated for each assembly.

$$M_{i,j} = \left(1 - \frac{RPD_{i,j} \cdot R_{local} \cdot F_{total}}{L_{i,j}}\right) \cdot 100$$

Each type of plant licensing may include one or more of these limits that are verified typically to meet LOCA and/or DNBR limiting transient events. Each of the components used in calculating the peaking margin is discussed in the following sections.

7.1.1 $M_{i,j,k}$

The peaking margin is expressed as the percent difference between the measured peak and the peaking limit at that location. A positive number indicates that the peak is below the limit and zero indicates that the peak has reached the limit. This margin includes both uncertainty and other factors to account for known effects not modeled by the core simulator to provide appropriate assurance of fuel integrity.

7.1.2 $RPD_{i,j,k}$

The nodal relative power densities, each of which represents a nodal volume rather than a single fuel pin, is taken from the kriging process.

7.1.3 R_{local}

Since the $RPD_{i,j,k}$ is a nodal power, the ratio of the pin power to the nodal power, R_{local}, is calculated by the core simulator and applied to $RPD_{i,j,k}$ to find the peak pin power in each location.

7.1.4 F_{total}

This factor is a combination of all of the statistically and non-statistically quantified peaking factors and uncertainties that are not already included in the generation of the peaking limit, including allowances for effects that are not modeled but are known to be present, such as spacer grid peaking factors. The statistically and non-statistically quantified components are combined separately and then multiplied together to determine the total peaking augmentation factor.

$$F_{total} = F_{stat} \cdot F_{mult}$$

7.1.4.1 F_{stat}

The total uncertainty factors which are statistically quantified are combined based on that quantification.

$$F_{stat} = 1 + k_{95/95} \cdot \left(\sum_i \left(\frac{\sigma_i}{k_i} \right)^2 \right)^{\frac{1}{2}}$$

where

F_{stat} = the combined uncertainty factor

$k_{95/95}$ = tolerance factor (95/95) for a normal distribution

σ_i = uncertainty factors (see Table 7-1 for examples)

k_i = 95/95 tolerance factors used to determine the original individual uncertainties

Values of the 95/95 tolerance limit, $k_{95/95}$, are linearly interpolated from the data in reference [11] using the calculated number of degrees of freedom, N_t. The Welch-Satterthwaite equation [12] is used to calculate an approximation to the effective degrees of freedom.

$$N_t = \frac{\left[\sum_i \left(\frac{\sigma_i}{k_i} \right)^2 \right]^2}{\sum_i \frac{\left(\frac{\sigma_i}{k_i} \right)^4}{N_i}}$$

Typical factors that could be included in this component are described in Table 7-1. The actual effects included will be consistent with the licensing basis of the particular plant where SUPR-FMTS is applied.

Table 7-1 Statistically Quantified Effects Included in the Total Peaking Factor

The values of these components depend on manufacturing processes, specific fuel designs, detector layouts and other implementation-specific details. Typical values are provided in the example in Appendix C.

7.1.4.2 F_{mult}

These factors are multiplied together and are typically biases.

$$F_{mult} = \prod_{i} (1 + F_i)$$

Effects that could be included in this component are described in Table 7-2. These generally account for known effects that have been quantified but are not included in the power distribution calculation model.

Table 7-2 Additional Effects Included in the Total Peaking Factor

[ ]

These are the presently applied typical peaking uncertainty and augmentation factors. If another factor is found to be required, it can be included in the calculation of the peaking limit. If it is not included there, it will be included in F_{total}. If it is statistically quantified, it is included in the statistical portion of this factor or, if not statistically quantified, in the multiplicative portion of this factor.

7.1.5 $L_{i,j,k}$

These are the power peaking limits necessary to provide assurance of fuel integrity during Condition I and II events. If any power peaking uncertainties are not applied in the calculation of these limits, then they are applied in the F_{total} factor described above.

7.1.6 *Margin Monitoring*

These peaking margins are monitored every few minutes by SUPR-FMTS. If either the total or planar type of margin drops below zero, either the power distribution must be changed (primarily by control rod movements) to obtain positive margin, or the power level must be reduced in the same time-frame and amount as is required by the present plant Technical Specifications for the LCO power peaking actions. Technical Specification changes are required to replace power distribution related LCO limits on power imbalance, quadrant power tilt, and rod insertion with peaking margin monitoring via FMTS when FMTS is in use.

7.2 *TIP Flux Map Interval Modification Requirements*

This section describes the modifications required to the present Technical Specifications for plants where a movable detector system is used in order to accommodate possible longer periods between detailed flux maps afforded by the SUPR-FMTS methodology. Such plants have Technical Specifications that require monthly power maps to monitor the total and planar power distribution.

When the SUPR-FMTS methodology is applied to a movable detector system, the power peaking is monitored (every one to two minutes) and the differences between the online simulator and the thermocouple and excore detector system measurements are frequently monitored and any increasing differences are factored into the margin calculation. This is done through the RPD Check method, which incorporates a dynamically quantified deviation that grows if the thermocouple and excore measurements diverge from similar values derived from the SUPR-FMTS measured power distribution, as described in Section 4.3.5 and Section 7.1.4.1. As $\sigma^{C}_{i,j,k}$ increases, the margins to the peaking limits will decrease. This peaking margin will be trended to estimate the time when the reduced margin will begin to restrict operability at the operating power level. Before this occurs, another flux map can be taken to restore indicated margins or the power level can be reduced. This restoration of margin is the expected outcome because much of the margin reduction will be due to instrument drift and the flux map will be used to re-calibrate and eliminate the differences. If the margin decrease is not due mainly to instrument drift but rather to an unanticipated problem with the core power distribution, then the flux map will indicate that. In either case, adequate margin to the peaking limits is preserved.

The Technical Specifications are required to be modified so that with SUPR operating, the monthly surveillance using the flux map required in the Technical Specifications is replaced by the use of the power distribution from SUPR-FMTS along with the continuous online direct margin monitoring and the monitoring of the adjusted kriging variance. The monthly requirement for a flux map is changed to the projected time when the peaking margin becomes insufficient to support continued operation at that power.

7.3 *SUPR-FMTS System Monitoring*

The periodic power distribution monitoring required by present Technical Specifications provides surveillance of the operation of the core to indicate when the LCO limits may not preserve the fuel integrity during condition I and II events. Since, with SUPR-FMTS, the power distribution is monitored every few minutes and operation is limited to within the power distribution limits, a means is provided to monitor the performance of SUPR-FMTS on the same frequency as the power distribution monitoring. This is accomplished by comparing the adjusted kriging process variance ($(sigma^{C)^2}_{i,j,k}$ or ADJKPV) to limits supplied in the COLR at the same frequency as the F_Q and $F^N_{\Delta H}$ monitoring. The adjusted kriging process variance is a quantification of the differences between the power distribution calculated by the core simulator and the measured power distribution. It also reflects the variance augmentation produced by the RPD Check methodology. This augmentation provides a conservative check on the operation of SUPR-FMTS since a portion of the variance increase will probably be due to excore and thermocouple signal drift rather than deviation of the core from the planned depletion. In addition, ADJKPV is included as a penalty in the FMTS calculation of margin to the F_Q and $F^N_{\Delta H}$ limits, thereby decreasing the peaking margin and further restricting operation as the variance increases. For reactors using Traveling Incore Probes (TIPs), this will mandate that a new flux map be taken at the appropriate time to reduce ADJKPV. In time periods that see little change in the power distribution and little change in the thermocouple and excore measurements, the time between required flux maps could be extended to many months. In periods where there is significant change in these parameters, a flux map could be required more frequently. In either case, the required period is determined by the measured degradation of the system rather than by a fixed schedule.

8.0 REFERENCES

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Appendix A EXAMPLE KRIGING AND VARIANCE CALCULATION

This section will present an example calculation of the best estimate RPD, $\hat{y}$ in Chapter 4 , and the process variance, σ^2. While the kriging models include up to four dimensions (three spatial and one temporal), this example will be done in in the x,y plane to simplify the presentation. The vector notation is also modified from Chapter 4 as only one kriging model (one node) is calculated in this appendix. Thus the x values are scalars rather than vectors.

The input data are shown below. Figure A-1 shows the core simulator results for one axial node level at around three-quarters of the core height. Figure A-2 shows the corresponding measurement data translated to nodal power with spacer grid effects removed.

Node (6,10) will be evaluated in the example calculation. The range parameter, θ, is equal to **[ ]** assembly widths in both radial directions. The shaded area denotes the "area of influence" corresponding to all nodes within **[ ]** of node (6,10).

First, the vector **r**(x_0) is calculated based on:

$$\mathbf{r}(x_0) = \begin{bmatrix} R(x_0, x_1) \\ \vdots \\ R(x_0, x_N) \end{bmatrix}$$

and **[**

]

Point x_0 is (6,10) while Table A-1 gives the coordinates of each x_i.

The **R** matrix is then calculated as:

Figure A-1 Example Core Simulator Data

[ ]

Figure A-2 Example Processed Measurement Data

[ ]

Table A-1 Example Correlation Vector

[

]

$$\mathbf{R} = \begin{bmatrix} R(x_1, x_1) & \cdots & R(x_N, x_1) \\ \vdots & & \vdots \\ R(x_1, x_N) & \cdots & R(x_N, x_N) \end{bmatrix}$$

The results are shown in Table A-2.

The final component is the residual vector, $(\mathbf{y}-\mathbf{g})$. Table A-3 shows the calculated residuals for the N locations, $\mathbf{g}$.

Evaluating $g(x_0)+\mathbf{r}(x_0)^{\mathrm{T}}\mathbf{R}^{-1}(\mathbf{y}-\mathbf{g})$ yields a value of **[ ]** Thus, at the measurement time, the best estimate RPD, $\hat{y}$, value for location (6,10) would be **[ ]**

The **R** matrix and residual $(\mathbf{y}-\mathbf{b})$ vector are already formed, thus the kriging variance is calculated as: **[**

]

Table A-2 Example Covariance Matrix

[ ]

Table A-3 Example Residual Vector

	(y – g)
1	0.076
2	0.106
3	0.065
4	0.086
5	0.076
6	0.082
7	0.082
8	0.087
9	0.063
10	0.067
11	0.054
12	0.063
13	0.063

For this example, $\hat{\sigma}^2$ is calculated to be **[** **]** or a standard deviation of approximately **[** **]**

Appendix B EXAMPLE TECHNICAL SPECIFICATION FOR SUPR-FMTS USE

Changes required to the Standard Technical Specifications (STS) for Babcock and Wilcox[1], Westinghouse[2], and Combustion Engineering[3] Plants to implement SUPR-FMTS are provided in the section.

B.1 *General Approach*

The general approach to implementing SUPR-FMTS in Technical Specifications is shown in Figure B-1. The upper portion of the figure shows the parameters that are limited to preserve the limits on power peaking. The lower part of the figure shows the parameters that are monitored to confirm proper operation of the system. The left side of the figure depicts the approach contained in the present Standard Technical Specifications and the right side shows how that is modified to implement SUPR-FMTS. In this approach, which applies to section 3.2 Power Distribution Limits, the indirect means of limiting power peaking, which is regulating rod position, axial power shaping rod position (if present), axial power imbalance, and quadrant power tilt limits are replaced by Relaxed LCO Limits for these parameters. This is possible because these parameters are used to limit the initial power peaking for multiple events, and the parameter limits to preserve the ejected rod prompt energy deposition and shutdown margin requirements can be less restrictive than the parameter limits required to preserve the Loss of Coolant Accident and loss of forced reactor coolant flow design criteria. The parameter limits to preserve the latter two design criteria are replaced with the direct limitation of

[1]NUREG-1430, Standard Technical Specifications Babcock and Wilcox Plants, Division of Regulatory Improvement Programs, U.S. Nuclear Regulatory Commission, Washington, DC, Vol. 1 and 2, Rev. 3.0, June 2004

[2]NUREG-1431, Standard Technical Specifications Westinghouse Plants, Division of Regulatory Improvement Programs, U.S. Nuclear Regulatory Commission, Washington, DC, Vol. 1 and 2, Rev. 3.0, June 2004

[3]NUREG-1432, Standard Technical Specifications Combustion Engineering Plants, Division of Regulatory Improvement Programs, U.S. Nuclear Regulatory Commission, Washington, DC, Vol. 1 and 2, Rev. 3.0, June 2004

Figure B-1 General Approach to SUPR-FMTS Implementation in Technical Specifications

margin to the peaking limits.

Since F_Q and $F^N_{\Delta H}$ are now limited directly, they are monitored with a frequency equivalent to the frequency with which the indirect parameters were monitored. This is usually a maximum of 15 minutes.

The present requirements to periodically measure F_Q and $F^N_{\Delta H}$ provide assurance that the core is operating as designed and that the indirect parameter limits are preventing the peaking limits from being exceeded. Under SUPR-FMTS, F_Q and $F^N_{\Delta H}$ are limited directly and frequently and the surveillance requirement is changed to monitor the performance of SUPR-FMTS to provide assurance that SUPR-FMTS is operating properly and therefore the peaking limits will not be exceeded. This new surveillance is accomplished by examining the SUPR-FMTS adjusted kriging process variance, called ADJKPV, for all locations in the core which have relative power densities greater than 1.0 and comparing the values with limits provided in the COLR. This is done with a frequency which is the same or higher than the frequency of the previous F_Q and $F^N_{\Delta H}$ measurements.

Since ADJKPV is a quantification of the difference between the measured and calculated power distribution, it is used to judge the performance of SUPR-FMTS. If the ADJKPV values exceed their limits at equilibrium conditions, then SUPR-FMTS must be declared inoperable and the system performance must be evaluated. Operation then changes to the Restricted LCO Limits provided in the COLR, which provides the same basis for operation as before SUPR-FMTS was implemented. Twelve hours are allowed for this change to provide adequate time to determine and correct the cause of the excessive variance. This is deemed prudent to avoid creating a situation which increases the peaking because the operator is required to make sudden changes in regulating rod position and since the amount of ADJKPV is included in the online margin calculation.

The SUPR-FMTS system can therefore be inoperable either because of hardware failure or because it fails the ADJKPV self-performance-check. In either case, the primary

Technical Specification action required when the system becomes inoperable is to begin use of the restricted LCO limits. This is because if the margins were greater than zero then F_Q and $F_{\Delta H}^N$ were within their limits when the system became inoperable. And, if the margins were less than zero then Technical Specification actions to reduce F_Q and $F_{\Delta H}^N$ to below their limits would have already been initiated.

The following are examples of how this general approach is applied, using the Standard Technical Specifications as the base. Modifications to each of these Technical Specifications and Bases will be presented separately. The changes are presented as deletions, which are indicated in gray text, and additions, which are indicated in red text with a change bar in the margin. Only those sections affected by the implementation of SUPR-FMTS are included here. To make the changes as clear as possible, an effort was made to show the present STS context unmodified for spacing and line breaks.

B.2 *Babcock and Wilcox Plants*

The following power distribution related Technical Specification modifications and accompanying Bases are required for Babcock and Wilcox Plants using Standard Technical Specifications.

B.2.1 *Technical Specifications*

3.2 POWER DISTRIBUTION LIMITS

3.2.1 Regulating Rod Insertion Limits

LCO 3.2.1 Regulating rod groups shall be within the physical insertion, sequence, and overlap limits specified in the COLR.

---NOTES---

1. Not required for any regulating rod repositioned to perform SR 3.1.4.2.

2. Relaxed limits specified in the COLR may be used when SUPR-FMTS is OPERABLE.

APPLICABILITY: MODES 1 and 2.

3.2.2 AXIAL POWER SHAPING ROD (APSR) Insertion Limits

LCO 3.2.2 APSRs shall be positioned within the limits specified in the COLR.

---NOTE---

Relaxed limits specified in the COLR may be used when SUPR-FMTS is OPERABLE.

APPLICABILITY: MODES 1 and 2.

3.2.3 AXIAL POWER IMBALANCE Operating Limits

LCO 3.2.3 AXIAL POWER IMBALANCE shall be maintained within the limits specified in the COLR.

-----NOTE-----
Relaxed limits specified in the COLR may be used when SUPR-FMTS is OPERABLE.

APPLICABILITY: MODE 1 with THERMAL POWER > 40% RTP.

3.2.4 QUADRANT POWER TILT (QPT)

LCO 3.2.4 QPT shall be maintained less than or equal to the steady state limits specified in the COLR.

-----NOTE-----
Relaxed limits specified in the COLR may be used when SUPR-FMTS is OPERABLE.

APPLICABILITY: MODE 1 with THERMAL POWER > [20]% RTP.

3.2.5 Power Peaking Factors

ACTIONS

CONDITION	REQUIRED ACTION		COMPLETION TIME
D. SUPR-FMTS INOPERABLE	D.1	Control the reactor core to comply with the Restricted LCO Limits specified in the COLR.	1 hour
		AND	
		Perform SR 3.2.5.1	24 hours

3.2.5 Power Peaking Factors

SURVEILLANCE REQUIREMENTS

SURVEILLANCE		FREQUENCY
SR 3.2.5.1	------------------------------NOTE------------------------------ Only required to be performed when specified in LCO 3.1.8, "PHYSICS TESTS Exceptions - MODE 1," or when complying with Required Actions of LCO 3.1.4, "CONTROL ROD Group Alignment Limits," LCO 3.2.1, "Regulating Rod Insertion Limits," LCO 3.2.2, "AXIAL POWER SHAPING ROD (APSR) Insertion Limits," LCO 3.2.3, "AXIAL POWER IMBALANCE Operating Limits," LCO 3.2.4, "QUADRANT POWER TILT (QPT)." --	
	Verify $F_Q(Z)$ and $F^N_{\Delta H}$ are within limits by using the Incore Detector System to obtain a power distribution map.	As specified by the applicable LCO(s)
	OR	
	------------------------------NOTE------------------------------ Only required to be performed when SUPR-FMTS is OPERABLE. --	
	Verify $F_Q(Z)$ and $F^N_{\Delta H}$ are within limits by using the SUPR-FMTS System	15 minutes
	AND	
	Verify ADJKPV(X,Y,Z) for nodes with Relative Power > 1.0 is less than the limits specified in the COLR.	15 minutes

B.2.2 *Bases*

B 3.2 POWER DISTRIBUTION LIMITS

B 3.2.1 Regulating Rod Insertion Limits

BASES

BACKGROUND

The insertion limits of the regulating rods are initial condition assumptions used in all safety analyses that assume rod insertion upon reactor trip. The insertion limits directly affect the core power distributions, the worth of a potential ejected rod, the assumptions of available SDM, and the initial reactivity insertion rate.

The applicable criteria for these reactivity and power distribution design requirements are described in 10 CFR 50, Appendix A, GDC 10, "Reactor Design," GDC-26, "Reactivity Control System Redundancy-and Capability," GDC 28, "Reactivity Limits" (Ref. 1), and in 10 CFR 50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light Water Nuclear Power Plants" (Ref. 2).

Limits on regulating rod insertion have been established, and all rod positions are monitored and controlled during power operation to ensure that the power distribution and reactivity limits defined by the design power peaking and SDM limits are not violated.

The regulating rod groups operate with a predetermined amount of position overlap, in order to approximate a linear relation between rod worth and rod position (integral rod worth). To achieve this approximately linear relationship, the regulating rod groups are withdrawn and operated in a predetermined sequence. The automatic control system controls reactivity by moving the regulating rod groups in sequence within analyzed ranges. The group sequence and overlap limits are specified in the COLR.

The regulating rods are used for precise reactivity control of the reactor. The positions of the regulating rods are normally controlled automatically by the automatic control system but can also be controlled manually. They are capable of adding reactivity quickly compared with borating or diluting the Reactor Coolant System (RCS).

The power density at any point in the core must be limited to maintain specified acceptable fuel design limits, including limits that ensure that the criteria specified in 10 CFR 50.46 (Ref. 2) are not violated. Together, LCO 3.2.1, "Regulating Rod Insertion Limits," LCO 3.2.2, "AXIAL POWER SHAPING ROD (APSR) Insertion Limits," LCO 3.2.3, "AXIAL POWER IMBALANCE Operating Limits," and LCO 3.2.4, "QUADRANT POWER TILT (QPT)," provide limits on control component operation and on monitored process variables to ensure that the core operates within the $F_Q(Z)$ and $F^N_{\Delta H}$ limits in the COLR.

Portions of these LCO limits may be replaced by the continuous monitoring of F_Q and $F^N_{\Delta H}$ provided by SUPR-FMTS, thereby providing for the use of a set of Relaxed LCO Limits.

Operation within the F_Q limits given
in the COLR prevents power peaks that would exceed the loss of coolant accident (LOCA) limits derived from the analysis of the Emergency Core Cooling Systems (ECCS). Operation within the $F^N_{\Delta H}$ limits given in the COLR prevents departure from nucleate boiling (DNB) during a loss of forced reactor coolant flow accident. In addition to the $F_Q(Z)$ and $F^N_{\Delta H}$ limits, certain reactivity limits are met by regulating rod insertion limits. The regulating rod insertion limits also restrict the ejected CONTROL ROD worth to the values assumed in the safety analysis and maintain the minimum required SDM in MODES 1 and 2.

This LCO is required to minimize fuel cladding failures that breach the primary fission product barrier and release fission products into the reactor coolant in the event of a LOCA, loss of flow accident, ejected rod accident, or other postulated accidents requiring termination by a Reactor Protection System trip function.

APPLICABLE SAFETY ANALYSES

The fuel cladding must not sustain damage as a result of normal operation (Condition 1) or anticipated operational occurrences (Condition 2). The LCOs governing regulating rod insertion, APSR position, AXIAL POWER IMBALANCE, and QPT preclude core power distributions that violate the following fuel design criteria:

a. During a large break LOCA, the peak cladding temperature must not exceed 2200Â°F (Ref. 2).

b. During a loss of forced reactor coolant flow accident, there must be at least 95% probability at the 95% confidence level (the 95/95 DNB criterion) that the hot fuel rod in the core does not experience a DNB condition (Ref. 1).

c. During an ejected rod accident, the fission energy input to the fuel must not exceed 280 cal/gm (Ref. 3).

d. The CONTROL RODS must be capable of shutting down the reactor with a minimum required SDM with the highest worth CONTROL ROD stuck fully withdrawn (Ref. 1).

Fuel cladding damage does not occur when the core is operated outside the conditions of these LCOs during normal operation. However, fuel cladding damage could result if an accident occurs with the simultaneous violation of one or more of the LCOs limiting the regulating rod position, the APSR position, the AXIAL POWER IMBALANCE, and the QPT. This potential for fuel cladding damage exists because changes in the power distribution can cause increased power peaking and correspondingly increased local linear heat rates (LHRs).

When F_Q and $F_{\Delta H}^N$ limits are monitored by SUPR-FMTS, design criteria a. and b. are preserved by limiting margin to the F_Q and $F_{\Delta H}^N$ peaking limits rather than by compliance with the regulating rod insertion, APSR position, AXIAL POWER IMBALANCE, and QPT limits.

The SDM requirement is met by limiting the regulating and safety rod insertion limits such that sufficient inserted reactivity is available in the rods to shut down the reactor to hot zero power with a reactivity margin that assumes that the maximum worth rod remains fully withdrawn upon trip (Ref. 4). Operation at the SDM based regulating rod insertion limit may also indicate that the maximum ejected rod worth could be equal to the limiting value.

Operation at the regulating rod insertion limits may cause the local core power to approach the maximum linear heat generation rate or peaking factor with the allowed QPT present.

The regulating rod and safety rod insertion limits ensure that the safety analysis assumptions for SDM, ejected rod worth, and power distribution peaking factors remain valid (Refs. 3, 5, and 6).

The regulating rod insertion limits LCO satisfies Criterion 2 of 10 CFR 50.36(c)(2)(ii).

LCO

The limits on CONTROL ROD sequence, including group overlap, and insertion positions as defined in the COLR, must be maintained because they ensure that the resulting power distribution is within the range of analyzed power distributions and that the SDM and ejected rod worth are maintained.

The overlap between regulating groups provides more uniform rates of reactivity insertion and withdrawal and is imposed to maintain acceptable power peaking during regulating rod motion.

Error adjusted maximum allowable setpoints for regulating rod insertion are provided in the COLR. The setpoints are derived by an adjustment of the measurement system independent limits to allow for THERMAL POWER level uncertainty and rod position errors.

Actual alarm setpoints implemented in the unit may be more restrictive than the maximum allowable setpoint values to provide additional conservatism between the actual alarm setpoint and the measurement system independent limit.

LCO 3.2.1 has been modified by a Note that suspends the LCO requirement for those regulating rods not within the limits of the COLR solely due to testing in accordance with SR 3.1.4.2, which verifies the freedom of the rods to move. This SR may require the regulating rods to move below the LCO limit, which would otherwise violate the LCO.

LCO 3.2.1 has been modified by a Note that provides for the use of Relaxed Regulating Rod Limits when SUPR-FMTS is operable.

B 3.2 POWER DISTRIBUTION LIMITS

B 3.2.2 AXIAL POWER SHAPING ROD (APSR) Insertion Limits

BASES

BACKGROUND

The insertion limits of the APSRs are initial condition assumptions in all safety analyses that are affected by core power distributions. The applicable criterion for these power distribution design requirements are 10 CFR 50, Appendix A, GDC 10, "Reactor Design" (Ref. 1), and 10 CFR 50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light Water Nuclear Power Plants" (Ref. 2).

Limits on APSR insertion have been established, and all APSR positions are monitored and controlled during power operation to ensure that the power distribution defined by the design power peaking limits is maintained.

The power density at any point in the core must be limited to maintain specified acceptable fuel design limits, including limits that meet the criteria specified in Reference 2. Together, LCO 3.2.1, "Regulating Rod Insertion Limits," LCO 3.2.2, "AXIAL POWER SHAPING ROD (APSR) Insertion Limits," LCO 3.2.3, "AXIAL POWER IMBALANCE Operating Limits," and LCO 3.2.4, "QUADRANT POWER TILT (QPT)," provide limits on control component operation and on monitored process variables to ensure that the core operates within the $F_Q(Z)$ and $F^N_{\Delta H}$ limits in the COLR.

Portions of these LCO limits may be replaced by the continuous monitoring of F_Q and $F^N_{\Delta H}$ provided by SUPR-FMTS, thereby providing for the use of a set of Relaxed LCO Limits.

Operation within the $F_Q(Z)$ limits given in the COLR prevents power peaks that exceed the loss of coolant accident (LOCA) limits derived from the analysis of the Emergency Core Cooling Systems (ECCS). Operation within the $F^N_{\Delta H}$ limits given in the COLR prevents departure from nucleate boiling (DNB) during a loss of forced reactor coolant flow accident. The APSRs are not required for reactivity insertion rate on trip or SDM and, therefore, they do not trip upon a reactor trip.

This LCO is required to minimize fuel cladding failures that would breach the primary fission product barrier and release fission products to the reactor coolant in the event of a LOCA, loss of flow accident, ejected rod accident, or other postulated accident requiring termination by a Reactor Protection System trip function.

APPLICABLE SAFETY ANALYSES

The fuel cladding must not sustain damage as a result of normal operation (Condition 1) or anticipated operational occurrences (Condition 2). Acceptance criteria for the safety and regulating rod insertion, APSR position, AXIAL POWER IMBALANCE, and QPT LCOs preclude core power distributions that violate the following fuel design criteria:

a. During a large break LOCA, the peak cladding temperature must not exceed 2200Â°F (Ref. 2),

b. During a loss of forced reactor coolant flow accident, there must be at least 95% probability at the 95% confidence level (the 95/95 DNB criterion) that the hot fuel rod in the core does not experience a DNB condition,

c. During an ejected rod accident, the fission energy input to the fuel must not exceed 280 cal/gm (Ref. 3), and

d. CONTROL RODS must be capable of shutting down the reactor with a minimum required SDM with the highest worth CONTROL ROD stuck fully withdrawn (GDC 26, Ref. 1).

When F_Q and $F^N_{\Delta H}$ limits are monitored by SUPR-FMTS, design criteria a. and b. are preserved by limiting margin to the F_Q and $F^N_{\Delta H}$ peaking limits rather than by compliance with the regulating rod insertion, APSR position, AXIAL POWER IMBALANCE, and QPT limits.

Fuel cladding damage does not occur when the core is operated outside these LCOs during normal operation. However, fuel cladding damage could result should an accident occur simultaneously with violation of one or more of these LCOs. This potential for fuel cladding damage exists because changes in the power distribution can cause increased power peaking and corresponding increased local linear heat rates.

Operation at the APSR insertion limits may approach the maximum allowable linear heat generation rate or peaking factor with the allowed QPT present.

The APSR insertion limits satisfy Criterion 2 of 10 CFR 50.36(c)(2)(ii).

LCO

The limits on APSR physical insertion as defined in the COLR must be maintained because they serve the function of controlling the power distribution within an acceptable range.

LCO 3.2.2 has been modified by a Note that provides for the use of Relaxed Axial Power Shaping Rod Limits when SUPR-FMTS is operable.

The fuel cycle design assumes APSR withdrawal at the effective full power days (EFPD) burnup window specified in the COLR. Prior to this window, the APSRs cannot be maintained fully withdrawn in steady state operation. After this window, the APSRs are not allowed to be reinserted for the remainder of the fuel cycle.

Error adjusted maximum allowable setpoints for APSR insertion are provided in the COLR. The setpoints are derived by adjustment of the measurement system independent limits to allow for THERMAL POWER level uncertainty and rod position errors.

Actual alarm setpoints implemented in the unit may be more restrictive than the maximum allowable setpoint values to allow for additional conservatism between the actual alarm setpoints and the measurement system independent limits.

B 3.2 POWER DISTRIBUTION LIMITS

B 3.2.3 AXIAL POWER IMBALANCE Operating Limits

BASES

BACKGROUND

This LCO is required to limit the core power distribution based on accident initial condition criteria.

The power density at any point in the core must be limited to maintain specified acceptable fuel design limits, including limits that satisfy the criteria specified in 10 CFR 50.46 (Ref. 1). This LCO provides limits on AXIAL POWER IMBALANCE to ensure that the core operates within the $F_Q(Z)$ and $F^N_{\Delta H}$ limits in the COLR. Portions of these LCO limits may be replaced by the continuous monitoring of F_Q and $F^N_{\Delta H}$ provided by SUPR-FMTS, thereby providing for the use of a set of Relaxed LCO Limits. Operation within the $F_Q(Z)$ limits given in the COLR prevents power peaks that exceed the loss of coolant accident (LOCA) limits derived from the analysis of the Emergency Core Cooling Systems (ECCS). Operation within the $F^N_{\Delta H}$ limits given in the COLR prevents departure from nucleate boiling (DNB) during a loss of forced reactor coolant flow accident.

This LCO is required to limit fuel cladding failures that breach the primary fission product barrier and release fission products into the reactor coolant in the event of a LOCA, loss of forced reactor coolant flow accident, or other postulated accident requiring termination by a Reactor Protection System trip function. This LCO limits the amount of damage to the fuel cladding during an accident by maintaining the validity of the assumptions in the safety analyses related to the initial power distribution and reactivity.

Fuel cladding failure during a postulated LOCA is limited by restricting the maximum linear heat rate (LHR) so that the peak cladding temperature does not exceed 2200Â°F (Ref. 2). Peak cladding temperatures > 2200Â°F cause severe cladding failure by oxidation due to a Zircaloy water reaction. Other criteria must also be met (e.g., maximum cladding oxidation, maximum hydrogen generation, coolable geometry, and long term cooling). However, peak cladding temperature is usually most limiting.

Proximity to the DNB condition is expressed by the departure from nucleate boiling ratio (DNBR), defined as the ratio of the cladding surface heat flux required to cause DNB to the actual cladding surface heat flux. The minimum DNBR value during both normal operation and anticipated transients is limited to the DNBR correlation limit for the particular fuel design in use and is accepted as an appropriate margin to DNB. The DNB correlation limit ensures that there is at least 95% probability at the 95% confidence level (the 95/95 DNB criterion) that the hot fuel rod in the core does not experience DNB.

The measurement system independent limits on AXIAL POWER IMBALANCE are determined directly by the reload safety evaluation analysis without adjustment for measurement system error and uncertainty. Operation beyond these limits could invalidate the assumptions used in the accident analyses regarding the core power distribution.

APPLICABLE SAFETY ANALYSES

The fuel cladding must not sustain damage as a result of normal operation (Condition 1) and anticipated operational occurrences (Condition 2). The LCOs based on power distribution, LCO 3.2.1, "Regulating Rod Insertion Limits," LCO 3.2.2, "AXIAL POWER SHAPING ROD (APSR) Insertion Limits," LCO 3.2.3, "AXIAL POWER IMBALANCE Operating Limits," and LCO 3.2.4, "QUADRANT POWER TILT (QPT)," preclude core power distributions that would violate the following fuel design criteria:

a. During a large break LOCA, peak cladding temperature must not exceed 2200Â°F (Ref. 1).

b. During a loss of forced reactor coolant flow accident, there must be at least a 95% probability at the 95% confidence level (the 95/95 DNB criterion) that the hot fuel rod in the core does not experience a DNB condition.

The regulating rod positions, the APSR positions, the AXIAL POWER IMBALANCE, and the QPT are process variables that characterize and control the three dimensional power distribution of the reactor core.

When F_Q and $F^N_{\Delta H}$ limits are monitored by SUPR-FMTS, design criteria a. and b. are preserved by limiting margin to the F_Q and $F^N_{\Delta H}$ peaking limits rather than by compliance with the regulating rod insertion, APSR position, AXIAL POWER IMBALANCE, and QPT limits.

Fuel cladding damage does not occur when the core is operated outside this LCO during normal operation. However, fuel cladding damage could result should an accident occur with simultaneous violation of one or more of the LCOs governing the four process variables cited above. This potential for fuel cladding damage exists because changes in the power distribution can cause increased power peaking and corresponding increased local LHRs.

LCO

The power distribution LCO limits have been established based on correlations between power peaking and easily measured process variables: regulating rod position, APSR position, AXIAL POWER IMBALANCE, and QPT.

LCO 3.2.3 has been modified by a Note that provides for the use of Relaxed AXIAL POWER IMBALANCE Limits when SUPR-FMTS is operable.

The AXIAL POWER IMBALANCE envelope contained in the COLR represents the setpoints for which the core power distribution would either exceed the LOCA LHR limits or cause a reduction in the DNBR below the Safety Limit during the loss of flow accident with the allowable QPT present and with the APSR positions consistent with the limitations on APSR withdrawal determined by the fuel cycle design and specified by LCO 3.2.2.

Operation beyond the power distribution based LCO limits for the corresponding ALLOWABLE THERMAL POWER and simultaneous occurrence of either the LOCA or loss of forced reactor coolant flow accident has an acceptably low probability. Therefore, if the LCO limits are violated, a short time is allowed for corrective action before a significant power reduction is required.

B 3.2 POWER DISTRIBUTION LIMITS

B 3.2.4 QUADRANT POWER TILT (QPT)

BASES

BACKGROUND

This LCO is required to limit the core power distribution based on accident initial condition criteria.

The power density at any point in the core must be limited to maintain specified acceptable fuel design limits, including limits that preserve the criteria specified in 10 CFR 50.46 (Ref. 1). Together, LCO 3.2.1, "Regulating Rod Insertion Limits," LCO 3.2.2, "AXIAL POWER SHAPING ROD (APSR) Insertion Limits," LCO 3.2.3, "AXIAL POWER IMBALANCE Operating Limits," and LCO 3.2.4, "QUADRANT POWER TILT (QPT)," provide limits on control component operation and on monitored process variables to ensure that the core operates within the F_Q and $F^N_{\Delta H}$ limits given in the COLR. Portions of these LCO limits may be replaced by the continuous monitoring of F_Q and $F^N_{\Delta H}$ provided by SUPR-FMTS, thereby providing for the use of a set of Relaxed LCO Limits. Operation within the F_Q limits given in the COLR prevents power peaks that exceed the loss of coolant accident (LOCA) limits derived by Emergency Core Cooling Systems (ECCS) analysis. Operation within the $F^N_{\Delta H}$ limits given in the COLR prevents departure from nucleate boiling (DNB) during a loss of forced reactor coolant flow accident.

This LCO is required to limit fuel cladding failures that breach the primary fission product barrier and release fission products to the reactor coolant in the event of a LOCA, loss of forced reactor coolant flow, or other accident requiring termination by a Reactor Protection System trip function. This LCO limits the amount of damage to the fuel cladding during an accident by maintaining the validity of the assumptions used in the safety analysis related to the initial power distribution and reactivity.

Fuel cladding failure during a postulated LOCA is limited by restricting the maximum linear heat rate (LHR) so that the peak cladding temperature does not exceed 2200Â°F (Ref. 2). Peak cladding temperatures > 2200Â°F cause severe cladding failure by oxidation due to a Zircaloy water reaction. Other criteria must also be met (e.g., maximum cladding oxidation, maximum hydrogen generation, coolable geometry, and long term cooling). However, peak cladding temperature is usually most limiting.

Proximity to the DNB condition is expressed by the departure from nucleate boiling ratio (DNBR), defined as the ratio of the cladding surface heat flux required to cause DNB to the actual cladding surface heat flux. The minimum DNBR value during both normal operation and anticipated transients is limited to the DNBR correlation limit for the particular fuel design in use, and is accepted as an appropriate margin to DNB. The DNBR correlation limit ensures that there is at least 95% probability at the 95% confidence level (the 95/95 DNB criterion) that the hot fuel rod in the core does not experience DNB.

The measurement system independent limits on QPT are determined directly by the reload safety evaluation analysis without adjustment for measurement system error and uncertainty. Operation beyond these limits could invalidate core power distribution assumptions used in the accident analysis. The error adjusted maximum allowable alarm setpoints (measurement system dependent limits) for QPT are specified in the COLR.

APPLICABLE SAFETY ANALYSES

The fuel cladding must not sustain damage as a result of normal operation (Condition 1) and anticipated operational occurrences (Condition 2). The LCOs based on power distribution (LCO 3.2.1, LCO 3.2.2, LCO 3.2.3, and LCO 3.2.4) preclude core power distributions that violate the following fuel design criteria:

a. During a large break LOCA, the peak cladding temperature must not exceed 2200Â°F (Ref. 3).

b. During a loss of forced reactor coolant flow accident, there must be at least 95% probability at the 95% confidence level (the 95/95 DNB criterion) that the hot fuel rod in the core does not experience a DNB condition.

When F_Q and $F_{\Delta H}^N$ limits are monitored by SUPR-FMTS, design criteria a. and b. are preserved by limiting margin to the F_Q and $F_{\Delta H}^N$ peaking limits rather than the regulating rod insertion, APSR position, AXIAL POWER IMBALANCE, and QPT limits.

QPT is one of the process variables that characterize and control the three dimensional power distribution of the reactor core.

Fuel cladding damage does not occur when the core is operated outside this LCO during normal operation. However, fuel cladding damage could result if an accident occurs with simultaneous violation of one or more of the LCOs governing the core power distribution. Changes in the power distribution can cause increased power peaking and correspondingly increased local LHRs.

The dependence of the core power distribution on burnup, regulating rod insertion, APSR position, and spatial xenon distribution is taken into account during the reload safety evaluation analysis. An allowance for QPT is accommodated in the analysis and resultant LCO limits. The increase in peaking taken for QPT is developed from a database of full core power distribution calculations (Ref. 4). The calculations consist of simulations of many power distributions with tilt causing mechanisms (e.g., dropped or misaligned CONTROL RODS, broken APSR fingers fully inserted, misloaded assemblies, and burnup gradients). An increase of < 2% peak power per 1% QPT is supported by the analysis, therefore a value of 2% peak power increase per 1% QPT is used to bound peak power increases due to QPT.

Operation at the AXIAL POWER IMBALANCE or rod insertion limits must be interpreted as operating the core at the maximum allowable $F_Q(Z)$ or $F^N_{\Delta H}$ peaking factors for accident initial conditions with the allowed QPT present.

QPT satisfies Criterion 2 of 10 CFR 50.36(c)(2)(ii).

LCO

The power distribution LCO limits have been established based on correlations between power peaking and easily measured process variables: regulating rod position, APSR position, AXIAL POWER IMBALANCE, and QPT. The regulating rod insertion limits and the AXIAL POWER IMBALANCE boundaries contained in the COLR represent the measurement system independent limits at which the core power distribution either exceeds the LOCA LHR limits or causes a reduction in DNBR below the safety limit during a loss of flow accident with the allowable QPT present and with an APSR position consistent with the limitations on APSR withdrawal determined by the fuel cycle design and specified by LCO 3.2.2.

LCO 3.2.4 has been modified by a Note that provides for the use of Relaxed Quadrant Power Tilt Limits when SUPR-FMTS is operable.

Operation beyond the power distribution based LCO limits for the corresponding allowable THERMAL POWER and simultaneous occurrence of one of a LOCA, loss of forced reactor coolant flow accident, or ejected rod accident has an acceptably low probability. Therefore, if these LCO limits are violated, a short time is allowed for corrective action before a significant power reduction is required.

The maximum allowable setpoints for steady state, transient, and maximum limits for QPT applicable for the full symmetrical Incore Detector System, Minimum Incore Detector System, and Excore Detector System are provided; the setpoints are given in the COLR. The setpoints for the three systems are derived by adjustment of the measurement system independent QPT limits given in the COLR to allow for system observability and instrumentation errors.

Actual alarm setpoints implemented in the plant may be more restrictive than the maximum allowable setpoint values to allow for additional conservatism between the actual alarm setpoint and the measurement system independent limit.

It is desirable for an operator to retain the ability to operate the reactor when a QPT exists. In certain instances, operation of the reactor with a QPT may be helpful or necessary to discover the cause of the QPT. The combination of power level restriction with QPT in each Required Action statement restricts the local LHR to a safe level, allowing movement through the specified applicability conditions in the exception to Specification 3.0.3.

B 3.2 POWER DISTRIBUTION LIMITS

B 3.2.5 Power Peaking Factors

BASES

BACKGROUND

The purpose of this LCO is to establish limits that constrain the core power distribution within design limits during normal operation (Condition 1) and during anticipated operational occurrences (Condition 2) such that accident initial condition protection criteria are preserved. The accident initial condition criteria are preserved by bounding operation at THERMAL POWER within specified acceptable fuel design limits.

$F_Q(Z)$ is a specified acceptable fuel design limit that preserves the initial conditions for the Emergency Core Cooling Systems (ECCS) analysis. $F_Q(Z)$ is defined as the maximum local fuel rod linear power density divided by the average fuel rod linear power density, assuming nominal fuel pellet and rod dimensions. Because $F_Q(Z)$ is a ratio of local power densities, it is related to the maximum local (pellet) power density in a fuel rod. Operation within the $F_Q(Z)$ limits given in the COLR prevents power peaking that would exceed the loss of coolant accident (LOCA) linear heat rate (LHR) limits derived from the analysis of the ECCS.

The $F_{\Delta H}^{N}$ limit is a specified acceptable fuel design limit that preserves the initial conditions for the limiting loss of flow transient. $F_{\Delta H}^{N}$ is defined as the ratio of the integral of linear power along the fuel rod on which the minimum departure from nucleate boiling ratio (DNBR) occurs to the average integrated rod power. Because $F_{\Delta H}^{N}$ is a ratio of integrated powers, it is related to the maximum total power produced in a fuel rod. Operation within the $F_{\Delta H}^{N}$ limits given in the COLR prevents departure from nucleate boiling (DNB) during a postulated loss of forced reactor coolant flow accident.

Measurement of the core power peaking factors using the Incore Detector System to obtain a three dimensional power distribution map provides direct confirmation that $F_Q(Z)$ and $F_{\Delta H}^{N}$ are within their limits, and may be used to verify that the power peaking factors remain bounded when one or more normal operating parameters exceed their limits.

When SUPR-FMTS is operable, $F_Q(Z)$ and $F_{\Delta H}^{N}$ are continuously monitored so that the power distribution can be maintained within the $F_Q(Z)$ and $F^N_{\Delta H}$ limits.

APPLICABLE SAFETY ANALYSES

The limits on $F_Q(Z)$ are determined by the ECCS analysis in order to limit peak cladding temperatures to 2200Â°F during a LOCA. The maximum acceptable cladding temperature is specified by 10 CFR 50.46 (Ref. 1). Higher cladding temperatures could cause severe cladding failure by oxidation due to a Zircaloy water reaction. Other criteria must also be met (e.g., maximum cladding oxidation, maximum hydrogen generation, coolable geometry, and long term cooling). However, peak cladding temperature is usually most limiting.

The limits on $F^N_{\Delta H}$ provide protection from DNB during a limiting loss of flow transient. Proximity to the DNB condition is expressed by the DNBR, defined as the ratio of the cladding surface heat flux required to cause DNB to the actual cladding surface heat flux. The minimum DNBR value during both normal operation and anticipated transients is limited to the DNBR correlation limit for the particular fuel design in use, and is accepted as an appropriate margin to DNB. The DNBR correlation limit ensures that there is at least 95% probability at the 95% confidence level (the 95/95 DNB criterion) that the hot fuel rod in the core does not experience DNB.

This LCO precludes core power distributions that violate the following fuel design criteria:

a. During a large break LOCA, peak cladding temperature must not exceed 2200Â°F (Ref . 1).

b. During a loss of forced reactor coolant flow accident, there must be at least 95% probability at the 95% confidence level (the 95/95 DNB criterion) that the hot fuel rod in the core does not experience a DNB condition.

The reload safety evaluation analysis determines limits on global core parameters that characterize the core power distribution. The primary parameters used to monitor and control the core power distribution are the regulating rod position, the APSR position, the AXIAL POWER IMBALANCE, and the QPT. Either these parameters can be used to monitor and control the core power distribution because their measurements are continuously observable or SUPR-FMTS can be used to directly and continuously monitor proximity to the $F_Q(Z)$ and $F^N_{\Delta H}$ limits. Limits are placed on these parameters to ensure that the core power peaking factors remain bounded during operation in MODE 1 with THERMAL POWER greater than 20% RTP. Nuclear design model calculational uncertainty, manufacturing tolerances (e.g., the engineering hot channel factor), effects of fuel densification and rod bow, and modeling simplifications (such as treatment of the spacer grid effects) are accommodated through use of peaking augmentation factors in the reload safety evaluation analysis.

When SUPR-FMTS is in use, the regulating rod position, the APSR position, the AXIAL POWER IMBALANCE, and the QPT limits are no longer required to limit the core power distribution to preserve design criteria a. and b. on a frequent basis and therefore they may be relaxed to to less restrictive values which are needed to preserve other design criteria such as reactivity or accident initial conditions. When SUPR-FMTS is inoperable, the regulating rod position, the APSR position, the AXIAL POWER IMBALANCE, and the QPT limits are restricted to also limit design criteria a. and b.

$F_Q(Z)$ and $F^N_{\Delta H}$ satisfy Criterion 2 of 10 CFR 50.36(c)(2)(ii).

LCO

This LCO for the power peaking factors $F_Q(Z)$ and $F^N_{\Delta H}$ ensures that the core operates within the bounds assumed for the ECCS and thermal hydraulic analyses. Verification that $F_Q(Z)$ and $F^N_{\Delta H}$ are within the limits of this LCO as specified in the COLR allows continued operation at THERMAL POWER when the Required Actions of LCO 3.1.4, "CONTROL ROD Group Alignment Limits," LCO 3.2.1, "Regulating Rod Insertion Limits," LCO 3.2.2, "AXIAL POWER SHAPING ROD Insertion Limits," LCO 3.2.3, "AXIAL POWER IMBALANCE Operating Limits," and LCO 3.2.4, "QUADRANT POWER TILT," are entered. Conservative THERMAL POWER reductions are required if the limits on $F_Q(Z)$ and $F^N_{\Delta H}$ are exceeded. Verification that $F_Q(Z)$ and $F^N_{\Delta H}$ are within limits is also required during MODE 1 PHYSICS TESTS per LCO 3.1.8, "PHYSICS TESTS Exceptions - MODE 1."

Measurement uncertainties are applied when $F_Q(Z)$ and $F^N_{\Delta H}$ are determined using the Incore Detector System. The measurement uncertainties applied to the measured values of $F_Q(Z)$ and $F^N_{\Delta H}$ account for uncertainties in observability and instrument string signal processing.

Uncertainties are applied to the power distribution measured by SUPR-FMTS to preserve the $F_Q(Z)$ and $F^N_{\Delta H}$ limits. One is the dynamic variance of the SUPR-FMTS methodology, which is calculated by the system based on the number and type of power distribution measurement instruments being used. Another is a static uncertainty that is quantified by an analysis of the specific core and control rod geometry and power distribution measurement instrument geometry. In addition, the measured peak is augmented by other known bias factors.

ACTIONS

When SUPR-FMTS is inoperable, the operator must take care in interpreting the relationship of the power peaking factors $F_Q(Z)$ and $F^N_{\Delta H}$ to their limits. Limit values of $F_Q(Z)$ and $F^N_{\Delta H}$ in the COLR may be expressed in either LHR or in peaking units. Because $F_Q(Z)$ and $F^N_{\Delta H}$ are power peaking factors, constant LHR is maintained as THERMAL POWER is reduced, thereby allowing power peaking to be increased in inverse proportion to THERMAL POWER. Therefore, the $F_Q(Z)$ and $F^N_{\Delta H}$ limits increase as THERMAL POWER decreases (assuming $F_Q(Z)$ and $F^N_{\Delta H}$ are expressed in peaking units) so that a constant LHR limit is maintained.

When SUPR-FMTS is operable, a three-dimensional power distribution is produced based on all available data related to power distribution and the proximity of this power distribution to the $F_Q(Z)$ and $F^N_{\Delta H}$ peaking limits is monitored. When either type of limit is exceeded, the respective actions specified for exceeding that limit must be taken.

SURVEILLANCE REQUIREMENTS

SR 3.2.5.1

Core monitoring is performed using the SUPR-FMTS system, when operable. The peaking margin is monitored and is prevented from becoming negative by changing soluble boron to move control rods, by the use of APSR movement, or by reduction in THERMAL POWER. When SUPR-FMTS is inoperable, core monitoring is performed using the Incore Detector System to obtain a three dimensional power distribution map. Maximum values of $F_Q(Z)$ and $F^N_{\Delta H}$ obtained from this map may then be compared with the $F_Q(Z)$ and limits in the COLR to verify that the limits have not been exceeded. Measurement of the core power peaking factors in this manner may be used to verify that the measured values of $F_Q(Z)$ and $F^N_{\Delta H}$ remain within their specified limits when one or more of the limits specified by LCO 3.1.4, LCO 3.2.1, LCO 3.2.2, LCO 3.2.3, or LCO 3.2.4 is exceeded, or when LCO 3.1.8 is applicable. If $F_Q(Z)$ and $F^N_{\Delta H}$ remain within their limits when one or more of these parameters exceed their limits, operation at THERMAL POWER may continue because the true initial conditions (the power peaking factors) remain within their specified limits.

The SUPR-FMTS produced power distribution variance, ADJKPV(X,Y,Z), is the variance of the measurement and core simulator. Periodic comparison of this parameter with the expected values provided in the COLR provides assurance that SUPR-FMTS is operating as expected.

Because the limits on $F_Q(Z)$ and $F^N_{\Delta H}$ are preserved when the parameters specified by LCO 3.1.4, LCO 3.2.1, LCO 3.2.2, LCO 3.2.3, and LCO 3.2.4 are within their limits, a Note is provided in the SR to indicate that monitoring of the power peaking factors is required only when complying with the Required Actions of these LCOs and when LCO 3.1.8 is applicable.

Frequencies for monitoring of the power peaking factors and ADJKPV(X,Y,Z) are specified in the Action statements of the individual LCOs. These Frequencies are reasonable based on the low probability of a limiting event occurring simultaneously with either $F_Q(Z)$ or $F^N_{\Delta H}$ exceeding its limit, and they provide sufficient time for the operator to obtain a power distribution map from the Incore Detector System when SUPR-FMTS is not operable. When SUPR-FMTS is operable, the monitoring is more frequent since the $F_Q(Z)$ or $F^N_{\Delta H}$ limits are being limited directly rather than by the indirect means of limiting the regulating rod position, the APSR position, the AXIAL POWER IMBALANCE, and the QPT limits, which, because their limits are independent of each other, can limit the power peaking to less than the $F_Q(Z)$ or $F^N_{\Delta H}$ limit values. Indefinite THERMAL POWER operation in a Required Action of LCO 3.1.4, LCO 3.2.1, LCO 3.2.2, LCO 3.2.3, or LCO 3.2.4 is not permitted, in order to limit the potential for exceeding both the power peaking factors assumed in the accident analyses due to operation with unanalyzed core power distributions and spatial xenon distributions beyond their analyzed ranges.

B.3 *Westinghouse Plants*

The following power distribution related Technical Specification modifications and accompanying Bases are required for Westinghouse Plants using Standard Technical Specifications. The Standard Technical Specifications reflect three different operating methodologies, CAOC-F_{XY} (Constant Axial Offset Control), RAOC-W(Z) (Relaxed Axial Offset Control), and CAOC-W(Z) (Constant Axial Offset Control). Since operation with SUPR-FMTS will be similar to RAOC, the changes provided here are based on RAOC methodology Standard Technical Specifications.

B.3.1 *Technical Specifications*

3.2 POWER DISTRIBUTION LIMITS

3.2.1B Heat Flux Hot Channel Factor ($F_Q(Z)$ (RAOC-W(Z) Methodology)

LCO 3.2.1B — $F_Q(Z)$, as approximated by $F_Q^C(Z)$ and $F_Q^W(Z)$, shall be within the limits specified in the COLR.

APPLICABILITY: MODE 1.

ACTIONS

CONDITION	REQUIRED ACTION	COMPLETION TIME
D. SUPR-FMTS INOPERABLE	D.1 Control the reactor core to comply with the Restricted LCO Limits specified in the COLR. AND Perform SR 3.2.1.1	1 hour 24 hours

SURVEILLANCE REQUIREMENTS

--NOTE--
During power escalation at the beginning of each cycle, THERMAL POWER may be increased until an equilibrium power level has been achieved, at which a power distribution map is obtained.

SURVEILLANCE		FREQUENCY
SR 3.2.1.1	Verify $F_Q^C(Z)$ is within limit.	Once after each refueling prior to THERMAL POWER exceeding 75% RTP AND Once within [12] hours after achieving equilibrium conditions after exceeding, by ≥ 10% RTP, the THERMAL POWER at which $F_Q^C(Z)$ was last verified AND 31 EFPD thereafter
	OR -------------------------------NOTE------------------------------- Only required to be performed when SUPR-FMTS is OPERABLE. -- Verify $F_Q^C(Z)$ is within limits by using the SUPR-FMTS System	15 minutes

<u>AND</u>	
Verify ADJKPV(X,Y,Z) for nodes with Relative Power > 1.0 is less than the limits specified in the COLR.	15 minutes
<u>AND</u>	
Verify measured values of $F_Q(Z)$ are within limits specified in the COLR.	before ADJKPV(X,Y,Z) exceeds its limit

SURVEILLANCE REQUIREMENTS

SURVEILLANCE		FREQUENCY
SR 3.2.1.2	------------------------------NOTE------------------------------ Only required if SUPR-FMTS is INOPERABLE. If measurements indicate that the maximum over z [$F_Q^C(Z)$ / K(Z)] has increased since the previous evaluation of $F_Q^C(Z)$: a. Increase $F_Q^W(Z)$ by the greater of a factor of [1.02] or by an appropriate factor specified in the COLR and reverify $F_Q^W(Z)$ is within limits or b. Repeat SR 3.2.1.2 once per 7 EFPD until either a. above is met or two successive flux maps indicate that the maximum over z [$F_Q^C(Z)$ / K(Z)] has not increased. --	
	Verify $F_Q^W(Z)$ is within limit.	Once after each refueling prior to THERMAL POWER exceeding 75% RTP <u>AND</u> Once within [12] hours after achieving equilibrium conditions after exceeding, by ≥ 10% RTP, the THERMAL POWER at which $F_Q^W(Z)$ was last verified <u>AND</u>

	31 EFPD thereafter

3.2.2 Nuclear Enthalpy Rise Hot Channel Factor ($F^N_{\Delta H}$)

LCO 3.2.2 $F^N_{\Delta H}$ shall be within the limits specified in the COLR.

APPLICABILITY: MODE 1.

ACTIONS

CONDITION	REQUIRED ACTION		COMPLETION TIME
D. SUPR-FMTS INOPERABLE	D.1	Control the reactor core to comply with the Restricted LCO Limits specified in the COLR.	1 hour
		<u>AND</u>	
		Perform SR 3.2.2.1	24 hours

SURVEILLANCE REQUIREMENTS

SURVEILLANCE		FREQUENCY
SR 3.2.2.1	Verify $F^N_{\Delta H}$ is within limits specified in the COLR.	Once after each refueling prior to THERMAL POWER exceeding 75% RTP AND 31 EFPD thereafter
	OR -----------------------------NOTE----------------------------- Only required to be performed when SUPR-FMTS is OPERABLE. --	
	Verify $F^N_{\Delta H}$ is within limits by using the SUPR-FMTS System	15 minutes
	AND	
	Verify ADJKPV(X,Y,Z) for nodes with Relative Power > 1.0 is less than the limits specified in the COLR.	15 minutes
	AND	
	Verify measured values of $F^N_{\Delta H}$ are within limits specified in the COLR.	before ADJKPV(X,Y,Z) exceeds its limit

3.2.3B AXIAL FLUX DIFFERENCE (AFD) (Relaxed Axial Offset Control (RAOC) Methodology)

LCO 3.2.3 The AFD in % flux difference units shall be maintained within the limits specified in the COLR.

---NOTE---

1. The AFD shall be considered outside limits when two or more OPERABLE excore channels indicate AFD to be outside limits.

2. Relaxed limits specified in the COLR may be used when SUPR-FMTS is OPERABLE.

APPLICABILITY: MODE 1 with THERMAL POWER ≥ 50% RTP.

SURVEILLANCE REQUIREMENTS

SURVEILLANCE		FREQUENCY
SR 3.2.3.1	Verify AFD within limits for each OPERABLE excore channel.	7 days
	OR	
	Verify AFD is within limits using SUPR-FMTS	15 minutes

B.3.2 *Bases*

B 3.2 POWER DISTRIBUTION LIMITS

B 3.2.1B Heat Flux Hot Channel Factor ($F_Q(Z)$ (RAOC-W(Z) Methodology)

BASES

BACKGROUND

The purpose of the limits on the values of $F_Q(Z)$ is to limit the local (i.e., pellet) peak power density. The value of $F_Q(Z)$ varies along the axial height (Z) of the core.

$F_Q(Z)$ is defined as the maximum local fuel rod linear power density divided by the average fuel rod linear power density, assuming nominal fuel pellet and fuel rod dimensions. Therefore, $F_Q(Z)$ is a measure of the peak fuel pellet power within the reactor core.

When SUPR-FMTS is operable, $F_Q(Z)$ and $F^N_{\Delta H}$ are directly and continuously monitored so that the power distribution can be maintained within the $F_Q(Z)$ and $F^N_{\Delta H}$ limits.

When SUPR-FMTS is inoperable, the global power distribution is limited by LCO 3.2.3, "AXIAL FLUX DIFFERENCE (AFD)," and LCO 3.2.4, "QUADRANT POWER TILT RATIO(QPTR)," which are directly and continuously measured process variables. These LCOs, along with LCO 3.1.6, "Control Bank Insertion Limits," maintain the core limits on power distributions on a continuous basis.

LCO

The Heat Flux Hot Channel Factor, $F_Q(Z)$, shall be limited by the following relationships:

$F_Q(Z) \leq (CFQ / P)\ K(Z)$ for $P > 0.5$

$F_Q(Z) \leq (CFQ / 0.5)\ K(Z)$ for $P \leq 0.5$

where: CFQ is the $F_Q(Z)$ limit at RTP provided in the COLR,

K(Z) is the normalized $F_Q(Z)$ as a function of core height provided in the COLR, and

P = THERMAL POWER / RTP

For this facility, the actual values of CFQ and K(Z) are given in the COLR; however, CFQ is normally a number on the order of [2.32], and K(Z) is a function that looks like the one provided in Figure B 3.2.1B-1.

For Relaxed Axial Offset Control operation, $F_Q(Z)$ is approximated by $F_Q^C(Z)$ and $F_Q^W(Z)$. Thus, both $F_Q^C(Z)$ and $F_Q^W(Z)$ must meet the preceding limits on $F_Q(Z)$.

When SUPR-FMTS is inoperable,
an $F_Q^C(Z)$ evaluation requires obtaining an incore flux map in MODE 1. From the incore flux map results we obtain the measured value ($F_Q^M(Z)$) of $F_Q(Z)$. Then,

$$F_Q^C(Z) = F_Q^M(Z)\ [1.0815]$$

where [1.0815] is a factor that accounts for fuel manufacturing tolerances and flux map measurement uncertainty.

$F_Q^C(Z)$ is an excellent approximation for $F_Q(Z)$ when the reactor is at the steady state power at which the incore flux map was taken.

The expression for $F_Q^W(Z)$ is:

$$F_Q^W(Z) = F_Q^C(Z)\ W(Z)$$

where W(Z) is a cycle dependent function that accounts for power distribution transients encountered during normal operation. W(Z) is included in the COLR. The $F_Q^C(Z)$ is calculated at equilibrium conditions.

When SUPR-FMTS is operable, $F_Q(Z)$ is directly and continuously monitored so that the power distribution can be maintained within limits. The measured peak is augmented by both SUPR-FMTS uncertainty factors and other known bias factors before comparison with the limit.

SURVEILLANCE REQUIREMENTS

SR 3.2.1.1
Verification that $F_Q^C(Z)$ is within its specified limits involves increasing $F_Q^M(Z)$ to allow for manufacturing tolerance and measurement uncertainties in order to obtain $F_Q^C(Z)$. Specifically, $F_Q^M(Z)$ is the measured value of $F_Q(Z)$ obtained from incore flux map results and $F_Q^C(Z) = F_Q^M(Z)$ [1.0815] (Ref. 4). $F_Q^C(Z)$ is then compared to its specified limits.

The limit with which $F_Q^C(Z)$ is compared varies inversely with power above 50% RTP and directly with a function called K(Z) provided in the COLR.

Performing this Surveillance in MODE 1 prior to exceeding 75% RTP ensures that the $F_Q^C(Z)$ limit is met when RTP is achieved, because peaking factors generally decrease as power level is increased.

If THERMAL POWER has been increased by ≥ 10% RTP since the last determination of $F_Q^C(Z)$, another evaluation of this factor is required [12] hours after achieving equilibrium conditions at this higher power level (to ensure that $F_Q^C(Z)$ values are being reduced sufficiently with power increase to stay within the LCO limits).

The Frequency of 31 EFPD is adequate to monitor the change of power distribution with core burnup because such changes are slow and well controlled when the plant is operated in accordance with the Technical Specifications (TS).

When SUPR-FMTS is operable, the $F_Q^M(Z)$ is maintained within the $F_Q(Z)$ limit and the surveillance verifies that the SUPR-FMTS is performing as expected. This is accomplished by comparing the $F_Q^M(Z)$ variance (ADJKPV) to the expected value provided in the COLR. If the variance exceeds the limit, then SUPR-FMTS is declared inoperable, the restricted AFD and QPTR limits are used, and $F_Q^M(Z)$ is verified to be within the Technical Specification limits with an incore flux map.

SR 3.2.1.2
The Frequency is changed under SUPR-FMTS because that methodology incorporates an automatic variance adjustment which is based on a comparison to frequently monitored assembly exit thermocouples and excore flux detectors and which is included in the calculation of the margin to the $F_Q(Z)$ limits. The need for a flux map is instead indicated by the variance, ADJKPV, exceeding the limits in the COLR. If SUPR-FMTS becomes INOPERABLE and it has been more than 31 EFPD since the last power distribution measurement, then the surveillane reverts to the other part of SR 3.2.1.2 and another measurement is required as soon as practical to meet the 31 EFPD frequency requirement.

B 3.2 POWER DISTRIBUTION LIMITS

B 3.2.2 Nuclear Enthalpy Rise Hot Channel Factor ($F^N_{\Delta H}$)

BASES

BACKGROUND

The purpose of this LCO is to establish limits on the power density at any point in the core so that the fuel design criteria are not exceeded and the accident analysis assumptions remain valid. The design limits on local (pellet) and integrated fuel rod peak power density are expressed in terms of hot channel factors. Control of the core power distribution with respect to these factors ensures that local conditions in the fuel rods and coolant channels do not challenge core integrity at any location during either normal operation or a postulated accident analyzed in the safety analyses.

$F^N_{\Delta H}$ is defined as the ratio of the integral of the linear power along the fuel rod with the highest integrated power to the average integrated fuel rod power. Therefore, $F^N_{\Delta H}$ is a measure of the maximum total power produced in a fuel rod.

$F^N_{\Delta H}$ is sensitive to fuel loading patterns, bank insertion, and fuel burnup. $F^N_{\Delta H}$ typically increases with control bank insertion and typically decreases with fuel burnup.

$F^N_{\Delta H}$ is not directly measurable but is inferred from a power distribution map obtained with the movable incore detector system. Specifically, the results of the three dimensional power distribution map are analyzed by a computer to determine $F^N_{\Delta H}$. This factor is calculated at least every 31 EFPD. However, during power operation, the global power distribution is monitored by LCO 3.2.3, "AXIAL FLUX DIFFERENCE (AFD)," and LCO 3.2.4, "QUADRANT POWER TILT RATIO (QPTR)," which address directly and continuously measured process variables.
The Restricted Limits in the COLR for the process variables are monitored when SUPR-FMTS is inoperable. When, SUPR-FMTS is operable, the Relaxed Limits in the COLR for the process variables are monitored and margins to $F_Q(Z)$ and $F^N_{\Delta H}$ are continuously monitored so that the power distribution can be maintained within these limits.

LCO

$F^N_{\Delta H}$ shall be maintained within the limits of the relationship provided in the COLR.

The $F^N_{\Delta H}$ limit identifies the coolant flow channel with the maximum enthalpy rise. This channel has the least heat removal capability and thus the highest probability for a DNB.

The limiting value of $F^N_{\Delta H}$, described by the equation contained in the COLR, is the design radial peaking factor used in the unit safety analyses.

A power multiplication factor in this equation includes an additional margin for higher radial peaking from reduced thermal feedback and greater control rod insertion at low power levels. The limiting value of is $F^N_{\Delta H}$ allowed to increase 0.3% for every 1% RTP reduction in THERMAL POWER.

When SUPR-FMTS is operable, $F_Q(Z)$ and $F^N_{\Delta H}$ are continuously monitored so that the power distribution can be maintained within limits.

SURVEILLANCE REQUIREMENTS

SR 3.2.2.1

The value of $F^N_{\Delta H}$ is determined by using the movable incore detector system to obtain a flux distribution map. A data reduction computer program then calculates the maximum value of $F^N_{\Delta H}$ from the measured flux distributions. The measured value of $F^N_{\Delta H}$ must be multiplied by 1.04 to account for measurement uncertainty before making comparisons to the $F^N_{\Delta H}$ limit.

After each refueling, $F^N_{\Delta H}$ must be determined in MODE 1 prior to exceeding 75% RTP. This requirement ensures that $F^N_{\Delta H}$ limits are met at the beginning of each fuel cycle.

The 31 EFPD Frequency is acceptable because the power distribution changes relatively slowly over this amount of fuel burnup. Accordingly, this Frequency is short enough that the $F^N_{\Delta H}$ limit cannot be exceeded for any significant period of operation.

When SUPR-FMTS is operable, the $F^N_{\Delta H}$ is maintained within the $F^N_{\Delta H}$ limit and the surveillance verifies that the SUPR-FMTS is performing as expected. This is accomplished by comparing the SUPR-FMTS variance (ADJKPV) to the expected value provided in the COLR. If the variance exceeds the limit, then SUPR-FMTS is declared inoperable, the restricted AFD and QPTR limits are used and a flux map is taken to determine if the variance is due to a real deviation between the core simulator and the core or to problems with the thermocouple data.

The Frequency is extended under SUPR-FMTS because that methodology incorporates an automatic variance adjustment which is based on a comparison to frequently monitored assembly exit thermocouples and excore flux detectors and which adjustment is included in the calculation of the margin to the $F^{N}_{\Delta H}$ limits. The need for a flux map is therefore indicated by the variance, ADJKPV, exceeding the limits in the COLR. If SUPR-FMTS becomes INOPERABLE and it has been more than 31 EFPD since the last power distribution measurement, then the surveillance reverts to the other part of SR 3.2.1.2 and another measurement is required as soon as practical to meet the 31 EFPD frequency requirement.

B 3.2 POWER DISTRIBUTION LIMITS

B 3.2.3B AXIAL FLUX DIFFERENCE (AFD) (Relaxed Axial Offset Control (RAOC) Methodology)

BASES

BACKGROUND

The purpose of this LCO is to establish limits on the values of the AFD in order to limit the amount of axial power distribution skewing to either the top or bottom of the core. By limiting the amount of power distribution skewing, core peaking factors are consistent with the assumptions used in the safety analyses. Limiting power distribution skewing over time also minimizes the xenon distribution skewing, which is a significant factor in axial power distribution control.

RAOC is a calculational procedure that defines the allowed operational space of the AFD versus THERMAL POWER. The AFD limits are selected by considering a range of axial xenon distributions that may occur as a result of large variations of the AFD. Subsequently, power peaking factors and power distributions are examined to ensure that the loss of coolant accident (LOCA), loss of flow accident, and anticipated transient limits are met. Violation of the AFD limits invalidate the conclusions of the accident and transient analyses with regard to fuel cladding integrity.

Portions of these LCO limits may be replaced by the continuous monitoring of F_Q and $F^N_{\Delta H}$ provided by SUPR-FMTS, thereby providing for the use of a set of Relaxed LCO Limits.

APPLICABLE SAFETY ANALYSES

The AFD is a measure of the axial power distribution skewing to either the top or bottom half of the core. The AFD is sensitive to many core related parameters such as control bank positions, core power level, axial burnup, axial xenon distribution, and, to a lesser extent, reactor coolant temperature and boron concentration.

The allowed range of the AFD is used in the nuclear design process to confirm that operation within these limits produces core peaking factors and axial power distributions that meet safety analysis requirements.

When SUPR-FMTS is operational, this function of the AFD limits is not required to preserve the LOCA and LOFA initial conditions and so a set of Relaxed AFD limits may be used.

LCO

The shape of the power profile in the axial (i.e., the vertical) direction is largely under the control of the operator through the manual operation of the control banks or automatic motion of control banks. The automatic motion of the control banks is in response to temperature deviations resulting from manual operation of the Chemical and Volume Control System to change boron concentration or from power level changes.

Signals are available to the operator from the Nuclear Instrumentation System (NIS) excore neutron detectors (Ref. 3). Separate signals are taken from the top and bottom detectors. The AFD is defined as the difference in normalized flux signals between the top and bottom excore detectors in each detector well. For convenience, this flux difference is converted to provide flux difference units expressed as a percentage and labeled as %Δ flux or %ΔI.

The AFD limits are provided in the COLR. Figure B 3.2.3B-1 shows typical RAOC AFD limits. The AFD limits for RAOC do not depend on the target flux difference. However, the target flux difference may be used to minimize changes in the axial power distribution.

Violating this LCO on the AFD could produce unacceptable consequences if a Condition 2, 3, or 4 event occurs while the AFD is outside its specified limits.

LCO 3.2.3B has been modified by a Note that provides for the use of Relaxed AFD Limits when SUPR-FMTS is operable.

B 3.2 POWER DISTRIBUTION LIMITS

B 3.2.4 QUADRANT POWER TILT RATIO (QPTR)

BASES

APPLICABLE SAFETY ANALYSES

This LCO precludes core power distributions that violate the following fuel design criteria:

a. During a large break loss of coolant accident, the peak cladding temperature must not exceed 2200Â°F (Ref. 1),

b. During a loss of forced reactor coolant flow accident, there must be at least 95% probability at the 95% confidence level (the 95/95 departure from nucleate boiling (DNB) criterion) that the hot fuel rod in the core does not experience a DNB condition,

c. During an ejected rod accident, the energy deposition to the fuel must not exceed 280 cal/gm (Ref. 2), and

d. The control rods must be capable of shutting down the reactor with a minimum required SDM with the highest worth control rod stuck fully withdrawn (Ref. 3).

When F_Q and $F_{\Delta H}^N$ limits are monitored by SUPR-FMTS, design criteria a. and b. are preserved directly rather than by limiting the regulating rod insertion, AXIAL POWER IMBALANCE, and QPT.

LCO

The QPTR limit of 1.02, at which corrective action is required, provides a margin of protection for both the DNB ratio and linear heat generation rate contributing to excessive power peaks resulting from X-Y plane power tilts. A limiting QPTR of 1.02 can be tolerated before the margin for uncertainty in $F_Q(Z)$ and $(F_{\Delta H}^N)$ is possibly challenged.

LCO 3.2.4 has been modified by a Note that provides for the use of Relaxed QPTR Limits when SUPR-FMTS is operable.

B.4 *Combustion Engineering Plants*

The following power distribution related Technical Specification modifications and accompanying Bases are required for Combustion Engineering Plants using Standard Technical Specifications. The Standard Technical Specifications reflect two different monitoring methodologies, Analog and Digital. Since operation with SUPR-FMTS will be similar to Digital, the changes provided here are based on Digital methodology Standard Technical Specifications. Furthermore, since the SUPR-FMTS is a computer-based monitoring system, similar to the Core Operating Limit Supervisory System (COLSS), references in the Standard Technical Specifications to COLSS were not changed to SUPR-FMTS to highlight only the Technical Specification changes necessary to implement SUPR-FMTS. In this context, COLSS is used to indicate the combination of the present COLSS functionality and the SUPR-FMTS. Since the SUPR-FMTS approach is similar to the COLSS, fewer changes are required to Combustion Engineering Technical Specifications to implement SUPR-FMTS than for other plant types.

B.4.1 *Technical Specifications*

3.2 POWER DISTRIBUTION LIMITS

3.2.1 Linear Heat Rate (LHR) (Digital)

LCO 3.2.1 LHR shall not exceed the limits specified in the COLR.

APPLICABILITY: MODE 1 with THERMAL POWER > 20% RTP.

ACTIONS

CONDITION	REQUIRED ACTION	COMPLETION TIME
D. SUPR-FMTS INOPERABLE	D.1 Control the reactor core to comply with the Restricted LCO Limits specified in the COLR. AND Perform SR 3.2.1.1 and SR 3.2.1.2	1 hour within 2 hours

SURVEILLANCE REQUIREMENTS

SURVEILLANCE		FREQUENCY
SR 3.2.1.3	------------------------------NOTE------------------------------ Only required to be performed when SUPR-FMTS is OPERABLE. -- Verify ADJKPV(X,Y,Z) for nodes with Relative Power > 1.0 is less than the limits specified in the COLR.	15 minutes

3.2.2 Planar Radial Peaking Factors (F_{xy}) (Digital)

LCO 3.2.2 The measured Planar Radial Peaking Factors ($F_{xy}^{C}(Z)$) shall be equal to or less than the Planar Radial Peaking Factors (F_{xy}). (These factors are used in the Core Operating Limit Supervisory System (COLSS) and in the Core Protection Calculators (CPCs)).

APPLICABILITY: MODE 1 with THERMAL POWER > 20% RTP.

ACTIONS

CONDITION	REQUIRED ACTION	COMPLETION TIME
B. SUPR-FMTS INOPERABLE	B.1 Control the reactor core to comply with the Restricted LCO Limits specified in the COLR. <u>AND</u> Perform SR 3.2.2.1	1 hour 24 hours

SURVEILLANCE REQUIREMENTS

SURVEILLANCE		FREQUENCY
SR 3.2.2.1	Verify measured $F_{xy}^{M}(Z)$ obtained using the Incore Detector System is equal to or less than the value of $F_{xy}^{C}(Z)$ used in the COLSS and CPCs.	Once after each fuel loading with THERMAL POWER > 40% RTP but prior to operations above 70% RTP AND 31 EFPD thereafter
SR 3.2.2.2	------------------------------NOTE------------------------------ Only required to be performed when SUPR-FMTS is OPERABLE. --- Verify ADJKPV(X,Y,Z) for nodes with Relative Power > 1.0 is less than the limits specified in the COLR.	15 minutes

3.2.5 AXIAL SHAPE INDEX (ASI) (Digital)

LCO 3.2.5 ASI shall be within the limits specified in the COLR.

---NOTE---

Relaxed limits specified in the COLR may be used when SUPR-FMTS is OPERABLE.

APPLICABILITY: MODE 1 with THERMAL POWER > 20% RTP.

B.4.2 *Bases*

B 3.2 POWER DISTRIBUTION LIMITS

B 3.2.1 Linear Heat Rate (LHR) (Digital)

BASES

ACTION	B.1 When ADJKPV is above the limits specified in the COLR, the system must be declared inoperable and the restricted limits applied.
SURVEILLANCE REQUIREMENTS	SR 3.2.1.3 The SUPR-FMTS produced power distribution variance, ADJKPV(x,y,z), is the variance of the measurement and the core simulator. Periodic comparison of this parameter with the expected values provided in the COLR provides assurance that SUPR-FMTS is operating as expected.

B 3.2 POWER DISTRIBUTION LIMITS

B 3.2.2 Planar Radial Peaking Factors (F_{xy}) (Digital)

BASES

ACTION	B.1 When ADJKPV is above the limits specified in the COLR, the system must be declared inoperable and the restricted limits applied.
SURVEILLANCE REQUIREMENTS	SR 3.2.2.2 The SUPR-FMTS produced power distribution variance, ADJKPV(x,y,z), is the variance of the measurement and the core simulator. Periodic comparison of this parameter with the expected values provided in the COLR provides assurance that SUPR-FMTS is operating as expected.

B 3.2 POWER DISTRIBUTION LIMITS

B 3.2.5 AXIAL SHAPE INDEX (ASI) (Digital)

BASES

BACKGROUND

The purpose of this LCO is to limit the core power distribution to the initial values assumed in the accident analysis. Operation within the limits imposed by this LCO either limits or prevents potential fuel cladding failures that could breach the primary fission product barrier and release fission products to the reactor coolant in the event of a loss of coolant accident (LOCA), loss of flow accident, ejected control element assembly (CEA) accident, or other postulated accident requiring termination by a Reactor Protection System (RPS) trip function. This LCO limits the amount of damage to the fuel cladding during an accident by ensuring that the plant is operating within acceptable conditions at the onset of a transient.

Portions of the ASI limit may be replaced by the continuous monitoring of the LHR and DNBR provided by SUPR-FMTS, thereby providing for the use of a set of Relaxed ASI Limits.

LCO

LCO 3.2.5 has been modified by a Note that provides for the use of Relaxed ASI Limits when SUPR-FMTS is operable.

Appendix C EXAMPLE APPLICATION

An example application of the methodology is given for the generation of the measured power distribution from the online core simulator and the movable incore detector (TIP) readings. The generation of the RPD variance at an intermediate time between TIP measurements based on the measured assembly exit thermocouples and excore detectors is also provided. An example calculation of peaking margin for the limiting location in the core based on the measured core power distribution and the adjusted variance is then provided. An example of F_Q and $F_{\Delta H}$ monitoring is provided. Sections C.1 through C.4 show the Statistical Universal Power Reconstruction (SUPR). Section C.5 shows the Fixed Margin Tech Specs (FMTS) application.

C.1 *Movable Incore Detector Results*

The traveling incore probes (TIPs) are used to measure the neutron flux in the monitored subset of fuel assembly locations. These readings are interpreted by presently used methods [2] and provide a set of relative powers. An example set of unprocessed and processed measured relative powers are shown in Figures C-1 and C-2. Note that the figures in this section only show five axial levels while flux maps are typically taken using 60 axial levels and monitoring is done using many more than five levels. The reduced data set is used for brevity, in actual operation many more axial levels can be accommodated. Also note that "0.000" values for measured parameters represent failed measurement locations.

Figure C-1 Example Unprocessed TIP Values (Raw Signals)

j \ i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1							0.099 0.158 0.188 0.210 0.214			0.103 0.168 0.198 0.223 0.225					
2			0.084 0.137 0.165 0.189 0.192			0.254 0.399 0.483 0.541 0.542		0.248 0.391 0.469 0.520 0.524							
3								0.214 0.452 0.524 0.573 0.580		0.290 0.463 0.551 0.616 0.620		0.287 0.421 0.502 0.565 0.569		0.087 0.143 0.171 0.194 0.194	
4		0.156 0.257 0.305 0.343 0.345	0.286 0.422 0.504 0.564 0.577					0.265 0.422 0.495 0.535 0.546							
5					0.310 0.446 0.534 0.604 0.615				0.320 0.482 0.568 0.621 0.621		0.317 0.447 0.535 0.601 0.606		0.312 0.462 0.553 0.623 0.629		
6	0.100 0.167 0.198 0.221 0.224		0.288 0.462 0.548 0.613 0.625			0.326 0.457 0.536 0.594 0.598		0.324 0.491 0.571 0.620 0.623						0.253 0.396 0.473 0.521 0.523	
7				0.292 0.467 0.535 0.593 0.596			0.318 0.457 0.533 0.593 0.597			0.306 0.497 0.570 0.621 0.627			0.299 0.431 0.512 0.572 0.577		
8	0.108 0.178 0.208 0.228 0.233		0.000 0.000 0.000 0.000 0.000		0.286 0.465 0.537 0.585 0.586		0.293 0.472 0.545 0.596 0.604			0.000 0.000 0.000 0.000 0.000		0.261 0.424 0.488 0.530 0.535	0.277 0.447 0.515 0.577 0.578	0.247 0.382 0.454 0.503 0.505	
9		0.000 0.000 0.000 0.000 0.000							0.323 0.464 0.542 0.603 0.610		0.322 0.478 0.560 0.608 0.614				0.095 0.152 0.179 0.199 0.200
10					0.298 0.483 0.566 0.626 0.635		0.290 0.486 0.567 0.629 0.637					0.317 0.448 0.528 0.589 0.598			
11	0.080 0.127 0.153 0.179 0.181				0.320 0.464 0.543 0.606 0.611			0.290 0.464 0.536 0.592 0.595			0.318 0.455 0.537 0.598 0.602				0.080 0.132 0.158 0.178 0.178
12						0.320 0.449 0.531 0.595 0.603			0.290 0.462 0.537 0.596 0.598			0.000 0.000 0.000 0.000 0.000			
13			0.173 0.344 0.417 0.473 0.475		0.312 0.462 0.551 0.619 0.622			0.275 0.450 0.516 0.566 0.568						0.078 0.143 0.170 0.192 0.192	
14			0.085 0.139 0.165 0.184 0.186				0.225 0.368 0.428 0.470 0.472			0.248 0.389 0.471 0.525 0.527		0.157 0.260 0.304 0.338 0.339			
15					0.078 0.128 0.154 0.174 0.176			0.088 0.171 0.204 0.222 0.227							

$k = 1$
$k = 2$
$k = 3$
$k = 4$
$k = 5$

Figure C-2 Example Processed TIP Values (RPDs)

j \ i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1							0.280 0.410 0.437 0.432 0.410			0.289 0.421 0.442 0.443 0.413					
2			0.229 0.346 0.371 0.361 0.339			0.935 1.442 1.454 1.384 1.217		0.912 1.389 1.421 1.372 1.214							
3								0.843 1.269 1.336 1.318 1.198		0.884 1.304 1.366 1.338 1.217		1.016 1.540 1.566 1.483 1.279		0.239 0.353 0.367 0.363 0.331	
4		0.469 0.699 0.746 0.715 0.641	1.019 1.553 1.590 1.500 1.276					0.772 1.097 1.174 1.179 1.102							
5					1.050 1.603 1.669 1.621 1.432				1.076 1.583 1.631 1.593 1.439		1.057 1.594 1.657 1.601 1.415		1.074 1.636 1.670 1.589 1.371		
6	0.286 0.418 0.447 0.444 0.412		0.882 1.303 1.361 1.342 1.233			1.111 1.632 1.675 1.649 1.482		1.095 1.589 1.649 1.611 1.443						0.923 1.388 1.423 1.371 1.221	
7				0.898 1.282 1.347 1.335 1.240			1.068 1.573 1.647 1.611 1.435			0.892 1.256 1.332 1.313 1.231			1.025 1.538 1.605 1.544 1.368		
8	0.330 0.477 0.519 0.515 0.480		0.000 0.000 0.000 0.000 0.000		0.839 1.186 1.238 1.223 1.148		0.871 1.235 1.281 1.279 1.188			0.000 0.000 0.000 0.000 0.000		0.769 1.083 1.157 1.151 1.076	0.873 1.264 1.300 1.286 1.199	0.893 1.342 1.377 1.331 1.207	
9		0.000 0.000 0.000 0.000 0.000							1.084 1.605 1.654 1.603 1.412		1.071 1.565 1.604 1.557 1.403				0.260 0.374 0.397 0.402 0.385
10					0.865 1.251 1.324 1.303 1.213		0.867 1.264 1.312 1.298 1.207					1.083 1.609 1.668 1.610 1.445			
11	0.218 0.335 0.351 0.350 0.327				1.086 1.615 1.668 1.591 1.397			0.842 1.199 1.248 1.232 1.143			1.069 1.591 1.634 1.565 1.386				0.229 0.340 0.354 0.354 0.339
12						1.090 1.631 1.681 1.614 1.440			0.891 1.287 1.332 1.305 1.224			0.000 0.000 0.000 0.000 0.000			
13			0.768 1.250 1.270 1.218 1.067		1.074 1.627 1.663 1.570 1.366			0.876 1.246 1.312 1.275 1.193						0.233 0.346 0.356 0.357 0.332	
14			0.236 0.346 0.367 0.361 0.336				0.718 1.035 1.078 1.082 0.991			0.913 1.397 1.412 1.363 1.210		0.472 0.686 0.708 0.697 0.634			
15					0.222 0.333 0.357 0.352 0.334			0.306 0.463 0.497 0.497 0.469							

$k = 1$
$k = 2$
$k = 3$
$k = 4$
$k = 5$

C.2 *Core Simulator Results*

The online core simulator is run with the same plant parameter values (temperatures, rod positions, burnup, and offset) as were present at the time the movable incore detectors were used to measure the power distribution in the subset of fuel assembly locations. An example set of calculated relative powers are shown in Figure C-3.

Figure C-3 Example Core Simulator Results

j \ i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1					0.234 0.332 0.345 0.340 0.315	0.297 0.415 0.430 0.424 0.394	0.290 0.401 0.419 0.420 0.399	0.345 0.483 0.502 0.499 0.470	0.300 0.413 0.432 0.432 0.410	0.298 0.416 0.431 0.427 0.398	0.240 0.339 0.353 0.350 0.327				
2			0.243 0.345 0.357 0.350 0.323	0.486 0.697 0.712 0.689 0.625	0.901 1.325 1.325 1.252 1.101	0.942 1.376 1.381 1.314 1.162	0.747 1.041 1.063 1.036 0.952	0.923 1.332 1.344 1.292 1.163	0.750 1.044 1.066 1.040 0.956	0.938 1.371 1.377 1.312 1.163	0.899 1.322 1.324 1.253 1.104	0.488 0.699 0.716 0.695 0.631	0.242 0.342 0.355 0.349 0.324		
3		0.244 0.346 0.359 0.354 0.327	0.832 1.221 1.222 1.158 1.025	1.032 1.514 1.514 1.419 1.232	1.107 1.624 1.626 1.523 1.317	0.918 1.278 1.301 1.260 1.143	1.065 1.530 1.548 1.478 1.313	0.902 1.243 1.267 1.236 1.137	1.073 1.542 1.559 1.488 1.321	0.915 1.274 1.298 1.258 1.143	1.100 1.614 1.618 1.519 1.316	1.028 1.507 1.508 1.416 1.231	0.833 1.223 1.223 1.159 1.025	0.244 0.346 0.358 0.351 0.324	
4		0.485 0.695 0.712 0.692 0.628	1.025 1.504 1.506 1.415 1.230	0.878 1.223 1.246 1.203 1.089	0.870 1.206 1.236 1.203 1.098	1.121 1.595 1.613 1.540 1.369	0.913 1.253 1.281 1.252 1.152	0.804 1.094 1.126 1.111 1.037	0.919 1.262 1.290 1.260 1.161	1.121 1.595 1.613 1.542 1.372	0.868 1.203 1.234 1.201 1.097	0.881 1.227 1.250 1.206 1.092	1.032 1.514 1.514 1.420 1.232	0.486 0.696 0.712 0.689 0.623	
5	0.239 0.339 0.353 0.350 0.326	0.898 1.321 1.323 1.253 1.104	1.098 1.611 1.617 1.518 1.316	0.867 1.202 1.233 1.201 1.097	1.094 1.576 1.604 1.532 1.356	0.899 1.240 1.269 1.238 1.135	1.099 1.558 1.579 1.517 1.360	0.855 1.172 1.201 1.178 1.088	1.105 1.565 1.585 1.524 1.366	0.902 1.242 1.273 1.243 1.139	1.095 1.577 1.604 1.532 1.355	0.870 1.206 1.237 1.203 1.097	1.106 1.623 1.625 1.522 1.316	0.900 1.324 1.323 1.251 1.099	0.233 0.332 0.344 0.339 0.314
6	0.297 0.415 0.431 0.426 0.398	0.937 1.370 1.377 1.312 1.163	0.914 1.273 1.298 1.258 1.144	1.120 1.593 1.612 1.541 1.372	0.901 1.242 1.273 1.244 1.140	1.120 1.593 1.615 1.548 1.381	0.898 1.240 1.270 1.240 1.134	1.107 1.577 1.600 1.536 1.372	0.898 1.240 1.270 1.240 1.135	1.120 1.592 1.615 1.548 1.381	0.899 1.240 1.269 1.238 1.133	1.120 1.594 1.611 1.539 1.367	0.916 1.276 1.299 1.257 1.140	0.938 1.372 1.378 1.310 1.158	0.295 0.413 0.428 0.422 0.392
7	0.300 0.413 0.432 0.432 0.410	0.749 1.044 1.066 1.040 0.956	1.072 1.540 1.558 1.487 1.321	0.916 1.258 1.286 1.257 1.157	1.104 1.565 1.585 1.524 1.366	0.898 1.240 1.270 1.240 1.135	1.095 1.573 1.604 1.538 1.366	0.884 1.217 1.253 1.228 1.131	1.095 1.573 1.604 1.538 1.366	0.898 1.240 1.270 1.239 1.133	1.098 1.557 1.577 1.516 1.358	0.910 1.251 1.279 1.249 1.149	1.060 1.524 1.543 1.472 1.307	0.740 1.034 1.057 1.029 0.945	0.287 0.396 0.415 0.415 0.393
8	0.342 0.479 0.499 0.496 0.467	0.921 1.329 1.342 1.290 1.161	0.902 1.241 1.266 1.234 1.136	0.803 1.093 1.125 1.110 1.037	0.856 1.173 1.202 1.179 1.089	1.109 1.580 1.601 1.538 1.374	0.884 1.217 1.253 1.228 1.131	0.803 1.101 1.141 1.126 1.046	0.885 1.218 1.254 1.230 1.132	1.107 1.577 1.599 1.536 1.372	0.855 1.171 1.200 1.177 1.087	0.800 1.090 1.121 1.106 1.032	0.896 1.236 1.261 1.229 1.130	0.911 1.318 1.332 1.280 1.150	0.336 0.471 0.491 0.487 0.458
9	0.289 0.399 0.417 0.417 0.397	0.744 1.038 1.060 1.033 0.948	1.064 1.530 1.548 1.477 1.312	0.915 1.256 1.284 1.254 1.154	1.101 1.561 1.581 1.520 1.362	0.903 1.247 1.276 1.245 1.138	1.096 1.576 1.606 1.539 1.367	0.884 1.217 1.253 1.228 1.131	1.095 1.574 1.604 1.538 1.366	0.898 1.240 1.270 1.240 1.134	1.102 1.562 1.583 1.521 1.363	0.912 1.253 1.282 1.252 1.152	1.063 1.529 1.548 1.477 1.311	0.737 1.030 1.053 1.026 0.941	0.274 0.379 0.397 0.397 0.377
10	0.296 0.414 0.428 0.423 0.393	0.939 1.373 1.379 1.311 1.159	0.918 1.277 1.300 1.258 1.142	1.122 1.597 1.613 1.540 1.369	0.901 1.241 1.270 1.239 1.135	1.123 1.597 1.618 1.551 1.383	0.899 1.241 1.271 1.241 1.135	1.110 1.580 1.602 1.538 1.374	0.900 1.242 1.272 1.241 1.135	1.121 1.593 1.615 1.548 1.381	0.901 1.241 1.272 1.242 1.139	1.115 1.588 1.607 1.536 1.366	0.907 1.265 1.290 1.250 1.136	0.923 1.354 1.364 1.298 1.149	0.289 0.406 0.422 0.417 0.388
11	0.233 0.331 0.344 0.339 0.314	0.900 1.323 1.322 1.250 1.098	1.106 1.622 1.623 1.522 1.315	0.870 1.206 1.236 1.203 1.097	1.095 1.578 1.605 1.533 1.356	0.905 1.246 1.278 1.247 1.143	1.107 1.569 1.588 1.526 1.368	0.861 1.180 1.209 1.184 1.093	1.101 1.561 1.581 1.519 1.362	0.900 1.241 1.270 1.239 1.134	1.093 1.575 1.602 1.530 1.353	0.864 1.198 1.230 1.198 1.094	1.091 1.601 1.608 1.509 1.307	0.889 1.310 1.313 1.244 1.094	0.237 0.335 0.349 0.346 0.322
12		0.485 0.696 0.711 0.688 0.623	1.031 1.512 1.512 1.417 1.230	0.877 1.222 1.244 1.202 1.088	0.867 1.202 1.232 1.200 1.096	1.120 1.594 1.613 1.541 1.372	0.917 1.258 1.287 1.256 1.157	0.804 1.094 1.125 1.111 1.037	0.916 1.257 1.285 1.255 1.155	1.121 1.596 1.613 1.540 1.368	0.869 1.204 1.235 1.201 1.095	0.875 1.220 1.243 1.200 1.086	1.019 1.496 1.499 1.408 1.224	0.482 0.690 0.708 0.688 0.624	
13		0.243 0.345 0.357 0.350 0.323	0.832 1.221 1.222 1.158 1.024	1.024 1.502 1.504 1.412 1.228	1.097 1.609 1.614 1.515 1.313	0.914 1.272 1.296 1.256 1.141	1.071 1.540 1.557 1.486 1.319	0.901 1.241 1.265 1.234 1.135	1.064 1.530 1.548 1.477 1.312	0.917 1.277 1.299 1.258 1.141	1.104 1.620 1.621 1.520 1.313	1.028 1.508 1.508 1.414 1.228	0.828 1.216 1.217 1.153 1.021	0.240 0.340 0.353 0.348 0.322	
14			0.244 0.347 0.360 0.354 0.327	0.484 0.693 0.711 0.690 0.626	0.896 1.318 1.320 1.250 1.101	0.935 1.368 1.375 1.310 1.161	0.748 1.043 1.065 1.038 0.954	0.921 1.329 1.341 1.289 1.160	0.744 1.037 1.059 1.032 0.948	0.939 1.373 1.377 1.310 1.159	0.899 1.321 1.321 1.249 1.097	0.484 0.694 0.710 0.687 0.622	0.242 0.344 0.355 0.349 0.321		
15					0.239 0.338 0.352 0.349 0.326	0.297 0.415 0.431 0.426 0.397	0.301 0.414 0.433 0.433 0.411	0.342 0.479 0.498 0.495 0.466	0.288 0.398 0.416 0.417 0.396	0.295 0.414 0.428 0.422 0.393	0.233 0.331 0.344 0.339 0.314				$k = 1$ $k = 2$ $k = 3$ $k = 4$ $k = 5$

C.3 *Kriging Results*

The detailed core simulator results and the processed TIP measurements are input to the kriging process. An example of the resulting relative power distribution is shown in Figure C-4. An example of the estimate of the variance (shown as standard deviation) is shown in Figure C-5.

C.4 *Variance Adjustment at Intermediate Times*

This section will show the adjustments made to the calculated variance at times without a direct power measurement. Data for the following figures uses the core simulator output and plant process data, including the thermocouple and excore detector readings, approximately two weeks after the flux map presented previously.

For systems where the power distribution is infrequently measured, such as movable or TIP systems, the more frequently measured power distribution-related parameters, such as excore detector and assembly exit thermocouple readings, are compared to values derived from the kriged power distribution at times between the infrequent measurements. When the difference between the expected and measured response no longer bound by the error estimate for the RPD, the kriging variance is augmented, as described in Section 4.3.

The measured excore detector voltage values are compared to values generated from the measured (kriged) power distribution using weighting factors that represent the contribution of each node in the core to the flux at the detector location.

Applying these weighting factors to the kriging results provides the example voltages (imbalance can be calculated if desired) and variance adjustment factors shown in Table C-1 below.

Applying the calculated mass flow rate from the previous TIP measurement time to the kriged RPD and plant parameters (inlet temperature, core thermal power, etc.), an expected set of thermocouple temperatures are calculated. Example calculated values

Figure C-4 Example Kriging Results

Figure C-5 Example Kriging Standard Deviation Results

Table C-1 Example Variance Adjustment Factors from the Excore Comparison

[ ]

are shown in Figure C-6 with the corresponding measured values and the variance adjustment, as discussed in Section 4.3.4. "0.0" values in Figure C-6 represent failed measurement locations.

The final adjusted variance is calculated according to Section 4.3.5. The resulting values - expressed as the standard deviation at one-sigma - are shown in Figure C-7.

C.5 *Peaking Margin to Limiting Criteria*

The total uncertainty is calculated and included in the calculation of margin to the LOCA and IC-DNB limits for LCO monitoring, as specified in Section 7.1.

C.5.1 *Uncertainty Calculation*

The total uncertainty is calculated by combining the uncertainty of all the components. This includes the adjusted kriging variance and the statistically quantified and multiplicative components. Table C-2 contains typical values for each component. These are combined with the nodal value from Figure C-7 above to produce the total statistically quantified uncertainty applied in calculating the peaking margin. For the peak node, at location (4, 6, 2), the adjusted process variance from SUPR is [ ] and the observability error is assumed to be [ ]

Figure C-6 Example Variance Adjustment Factors from the Thermocouple Comparison

[ ]

Figure C-7 Example Adjusted Kriging Standard Deviation Results

[

]

Table C-2 Uncertainties in the Components

[

]

[

] and for IC-DNB [

]

The multiplicative factors will address other effects, such as lack of explicit modeling of the fuel assembly spacer grids. In this example, a peaking factor of 1.015 will be used.

The total uncertainty factors to be applied in the margin calculations is the product of these. For LOCA [

] and for IC-DNB

[

]

C.5.2 *Margin Calculation*

The margin to the LCO limiting criteria, such as LOCA kW/ft limits and Initial Condition DNB peaking limits, is calculated from the power distribution from the kriging process and the total uncertainty calculated above. The LOCA margin is calculated for each monitored node, which excludes the top and bottom 10% of the core. The calculation of the peaking margin in percent for the peak node is shown below. The values of L are representative numbers for high-power locations from maneuvering analysis. [

]

The IC-DNB margin is for each fuel assembly as follows. [

]

To calculate the peaking margin for the peak pin in each core node, the ratio of the peak to average pin is obtained from the core simulator and applied to the measured nodal powers. An example set of peak-to-average pin power factors is shown in Figure C-8.

In this case, the margin is positive and no alarm is generated.

Figure C-8 Example Peak-to-Average Pin Power Factors

j \ i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1					2.087 2.070 2.040 2.015 1.992	1.774 1.825 1.796 1.762 1.718	1.680 1.707 1.684 1.657 1.622	1.611 1.611 1.596 1.581 1.562	1.628 1.641 1.623 1.601 1.579	1.752 1.795 1.769 1.737 1.696	2.103 2.098 2.067 2.040 2.012				
2			2.195 2.183 2.152 2.122 2.091	1.642 1.612 1.592 1.573 1.552	1.278 1.265 1.259 1.257 1.258	1.213 1.214 1.208 1.205 1.202	1.243 1.256 1.245 1.232 1.217	1.187 1.183 1.179 1.178 1.178	1.250 1.263 1.250 1.237 1.221	1.207 1.209 1.203 1.201 1.198	1.273 1.261 1.255 1.252 1.253	1.649 1.630 1.607 1.584 1.557	2.185 2.179 2.146 2.114 2.078		
3		2.178 2.161 2.129 2.098 2.066	1.339 1.315 1.309 1.307 1.306	1.144 1.139 1.139 1.140 1.140	1.072 1.070 1.070 1.069 1.076	1.056 1.066 1.060 1.056 1.051	1.090 1.093 1.093 1.092 1.090	1.087 1.109 1.101 1.093 1.084	1.087 1.089 1.090 1.089 1.087	1.073 1.068 1.069 1.070 1.074	1.072 1.069 1.069 1.070 1.077	1.141 1.135 1.136 1.137 1.137	1.339 1.314 1.309 1.307 1.306	2.193 2.178 2.147 2.118 2.086	
4		1.649 1.630 1.607 1.584 1.558	1.141 1.135 1.136 1.138 1.138	1.076 1.090 1.082 1.076 1.069	1.055 1.062 1.059 1.059 1.065	1.058 1.058 1.059 1.058 1.056	1.100 1.116 1.110 1.103 1.094	1.044 1.045 1.043 1.038 1.035	1.083 1.091 1.088 1.084 1.079	1.057 1.059 1.060 1.057 1.056	1.056 1.063 1.061 1.061 1.062	1.076 1.091 1.082 1.077 1.070	1.144 1.139 1.139 1.140 1.140	1.641 1.612 1.592 1.573 1.552	
5	2.104 2.100 2.069 2.041 2.013	1.274 1.261 1.255 1.253 1.253	1.073 1.069 1.069 1.070 1.077	1.056 1.064 1.061 1.061 1.062	1.069 1.070 1.069 1.069 1.069	1.036 1.044 1.044 1.044 1.044	1.077 1.080 1.074 1.073 1.078	1.064 1.074 1.073 1.071 1.068	1.077 1.080 1.074 1.073 1.078	1.040 1.042 1.041 1.041 1.046	1.069 1.070 1.069 1.068 1.069	1.054 1.061 1.059 1.059 1.064	1.072 1.070 1.070 1.070 1.076	1.278 1.265 1.259 1.257 1.258	2.087 2.070 2.041 2.016 1.993
6	1.753 1.796 1.770 1.738 1.696	1.207 1.209 1.203 1.201 1.198	1.072 1.068 1.068 1.070 1.074	1.057 1.059 1.060 1.057 1.056	1.039 1.042 1.041 1.041 1.045	1.053 1.054 1.057 1.056 1.051	1.036 1.040 1.040 1.040 1.040	1.070 1.079 1.072 1.071 1.076	1.036 1.041 1.040 1.039 1.039	1.053 1.054 1.057 1.055 1.051	1.036 1.044 1.044 1.044 1.044	1.058 1.058 1.059 1.057 1.056	1.057 1.067 1.061 1.056 1.051	1.214 1.215 1.209 1.206 1.203	1.778 1.828 1.799 1.765 1.721
7	1.629 1.643 1.625 1.603 1.579	1.250 1.262 1.250 1.236 1.220	1.087 1.089 1.089 1.089 1.087	1.084 1.092 1.089 1.085 1.080	1.077 1.080 1.074 1.073 1.078	1.036 1.040 1.040 1.039 1.038	1.069 1.073 1.070 1.069 1.067	1.087 1.099 1.095 1.089 1.084	1.069 1.072 1.070 1.068 1.066	1.036 1.040 1.040 1.040 1.040	1.077 1.080 1.074 1.073 1.078	1.101 1.116 1.110 1.104 1.095	1.092 1.094 1.094 1.093 1.091	1.244 1.257 1.245 1.233 1.218	1.686 1.712 1.689 1.662 1.627
8	1.614 1.615 1.600 1.584 1.565	1.187 1.184 1.180 1.178 1.179	1.087 1.109 1.101 1.093 1.084	1.044 1.044 1.043 1.038 1.035	1.064 1.074 1.073 1.071 1.068	1.069 1.078 1.072 1.071 1.076	1.087 1.099 1.095 1.089 1.084	1.049 1.052 1.049 1.045 1.038	1.087 1.099 1.094 1.089 1.084	1.070 1.079 1.072 1.071 1.076	1.065 1.075 1.074 1.072 1.069	1.044 1.045 1.043 1.038 1.034	1.086 1.108 1.100 1.092 1.083	1.188 1.185 1.181 1.180 1.180	1.624 1.625 1.609 1.593 1.575
9	1.680 1.707 1.684 1.657 1.622	1.245 1.257 1.246 1.233 1.219	1.091 1.094 1.093 1.092 1.091	1.101 1.116 1.110 1.104 1.095	1.077 1.080 1.074 1.073 1.078	1.037 1.042 1.041 1.041 1.041	1.070 1.073 1.071 1.069 1.067	1.088 1.100 1.095 1.089 1.085	1.069 1.073 1.070 1.069 1.067	1.037 1.042 1.041 1.040 1.039	1.077 1.080 1.074 1.073 1.078	1.085 1.093 1.090 1.086 1.081	1.088 1.090 1.090 1.090 1.088	1.258 1.269 1.257 1.243 1.228	1.701 1.707 1.686 1.666 1.644
10	1.776 1.826 1.797 1.763 1.719	1.213 1.215 1.208 1.205 1.202	1.057 1.066 1.060 1.055 1.050	1.058 1.057 1.059 1.058 1.057	1.036 1.044 1.044 1.044 1.045	1.053 1.054 1.057 1.055 1.051	1.036 1.041 1.040 1.039 1.039	1.069 1.078 1.072 1.071 1.075	1.036 1.040 1.040 1.040 1.040	1.053 1.054 1.057 1.055 1.051	1.039 1.042 1.041 1.041 1.045	1.057 1.058 1.060 1.057 1.056	1.074 1.068 1.069 1.071 1.074	1.211 1.213 1.207 1.204 1.202	1.774 1.816 1.789 1.758 1.716
11	2.070 2.052 2.024 2.002 1.983	1.278 1.265 1.259 1.257 1.258	1.072 1.070 1.070 1.070 1.077	1.055 1.061 1.059 1.060 1.065	1.069 1.070 1.069 1.069 1.070	1.040 1.044 1.042 1.042 1.047	1.076 1.080 1.073 1.072 1.077	1.064 1.075 1.074 1.072 1.069	1.076 1.080 1.074 1.073 1.078	1.036 1.044 1.044 1.044 1.044	1.069 1.070 1.069 1.069 1.070	1.056 1.063 1.061 1.060 1.061	1.073 1.070 1.070 1.070 1.078	1.274 1.262 1.256 1.254 1.254	2.104 2.100 2.069 2.041 2.014
12		1.642 1.612 1.592 1.573 1.552	1.144 1.139 1.139 1.140 1.140	1.076 1.090 1.082 1.076 1.069	1.056 1.063 1.061 1.061 1.062	1.057 1.058 1.060 1.058 1.056	1.085 1.093 1.090 1.086 1.081	1.045 1.045 1.044 1.039 1.034	1.101 1.117 1.111 1.105 1.096	1.059 1.058 1.059 1.058 1.057	1.055 1.062 1.059 1.060 1.065	1.076 1.090 1.082 1.076 1.069	1.142 1.136 1.136 1.138 1.138	1.649 1.630 1.608 1.585 1.557	
13		2.193 2.179 2.149 2.120 2.089	1.337 1.313 1.308 1.306 1.305	1.141 1.135 1.136 1.138 1.138	1.073 1.069 1.069 1.070 1.077	1.073 1.068 1.069 1.070 1.074	1.087 1.089 1.089 1.089 1.087	1.087 1.109 1.101 1.093 1.084	1.091 1.094 1.094 1.093 1.091	1.056 1.066 1.060 1.055 1.050	1.072 1.070 1.070 1.070 1.077	1.144 1.139 1.139 1.141 1.140	1.339 1.315 1.309 1.307 1.306	2.185 2.179 2.146 2.114 2.078	
14			2.187 2.169 2.135 2.103 2.068	1.650 1.631 1.608 1.585 1.558	1.274 1.261 1.255 1.253 1.253	1.207 1.209 1.203 1.201 1.198	1.250 1.263 1.250 1.236 1.221	1.187 1.184 1.179 1.178 1.179	1.245 1.257 1.246 1.233 1.218	1.213 1.215 1.208 1.205 1.202	1.279 1.265 1.259 1.257 1.258	1.642 1.613 1.592 1.574 1.553	2.196 2.183 2.152 2.124 2.092		
15					2.105 2.101 2.069 2.041 2.014	1.752 1.795 1.769 1.737 1.696	1.629 1.644 1.626 1.603 1.580	1.614 1.615 1.600 1.584 1.565	1.680 1.707 1.684 1.657 1.622	1.776 1.826 1.797 1.763 1.719	2.088 2.071 2.041 2.016 1.993				

$k = 1$
$k = 2$
$k = 3$
$k = 4$
$k = 5$

Appendix D EXAMPLE UNCERTAINTY ANALYSIS

This section provides an example of the analysis to quantify the system uncertainty values, σ^S, to be applied in the calculation of the margin to the peaking limit in Section 7.1 as part of F_{total} described in Section 7.1.4.

This example is artificial and represents a power increase in a fuel assembly in a position farthest from the TIPs. In actual application, the events described in Section 6.2 would be examined to determine the most limiting event. In addition, a range of failed thermocouples and TIP locations would be examined and the variation in σ^S would be quantified and applied as a function of those parameters. This particular example case only examined thermocouple failures.

A computer code called UAC has been written to perform the Monte Carlo analysis described in Section 6.3. In this analysis, a power distribution representing the desired plant conditions is generated by a core simulator code, NEMO. This power distribution is used for the assumed true power distribution. The Monte Carlo code then simulated operation of the SUPR-FMTS by applying the specified uncertainties to the measured parameters such as power level, rod position, incore, thermocouple, and excore measurements. This simulated plant data is used by the SUPR-FMTS to produce a "measured" power distribution. The ratio of the true to the simulated measured power distribution is calculated.

$$R_{i,j,k} = \frac{RPD^{True_{i,j,k}}}{RPD^{Meas_{i,j,k}}}$$

The amount this quantity exceeds 1.0 represents the amount that the true RPD is under-measured. This simulated power distribution measurement is repeated a sufficient number of times to build a distribution. In this example, **[** **]** trials were run but in actual application more may be run to obtain a better distribution.

For each nodal location in the core, the results of all the trials are examined with a D' normality test.[1] If the data for that node is deemed normal, an upper 95/95 tolerance limit is determined from the mean ratio and the standard deviation. If the data fails the normality test, a distribution-free tolerance limit is obtained from the data. In the example shown here, the ratios for the node are ranked and the 4th from the top, corresponding to a 95/95 tolerance limit for [ ] trials, is used for the tolerance limit for that node.

Since the margin calculation includes the Kriging Augmented Variance, $\sigma_{i,j,k}^{C}$, as described in Section 4.3.5, this factor is removed from the tolerance limits calculated above for each node.

$$R_{i,j,k}^{adj} = \frac{R_{i,j,k}}{1 + k \cdot \sigma_{i,j,k}^{C}}$$

The adjusted ratios for all nodes in the core are plotted against the true RPD in Figure D-1.

From this we see that a multiplicative factor of [ ] for σ^{S} combined with the application of $\sigma_{i,j,k}^{C}$ in the margin calculation will ensure that none of the high-powered or limiting nodes in the core will be greater than the true power 95% of the time with a 95% confidence. This analysis is repeated while including various amounts of random instrument failure. The resulting additional uncertainty factor, σ^{S}, above $\sigma_{i,j,k}^{C}$ required to provide the same assurance for a range, covering the percent of thermocouple instrument locations anticipated to fail without requiring a restriction in operation, is shown in Figure D-2.

[1]ANSI Standard ANS N15.15-1974 *American National Standard Assessment of the Assumption of Normality (Employing Individual Observed Values).*

Figure D-1 Adjusted Tolerance Limits for Nodes vs True RPD

[ ]

Figure D-2 Additional Uncertainty Factor vs Percentage of Failed Thermocouples