CPC Setpoint Analysis Methodology for APR1400

Revision 1

Non-Proprietary

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REVISION HISTORY

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ABSTRACT

This report describes Core Protection Calculator (CPC) setpoint analysis methodology for APR1400. The methodology is applied by combining uncertainties involved in the determination of the Local Power Density (LPD) and Departure from the Nucleate Boiling Ratio (DNBR) Limiting Safety System Settings (LSSS). CPC setpoint is determined by subtracting the overall uncertainty factors from the Safety Limit, but the overall uncertainty factors are cycle dependent. Therefore, overall uncertainty factors analyzed in the methods presented in this report are applied in CPC DNBR and LPD calculations for every cycle. The overall uncertainty factors assigned to LPD and DNBR establish that the adjusted LPD and DNBR are conservative at a 95/95 (probability/confidence) level throughout the core cycle, with respect to actual core conditions.

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ACRONYMS AND ABBREVIATIONS

ASI	axial shape index
BOC	beginning of cycle
BPPCC	boundary point power correlation coefficient
C-E	Combustion Engineering
CEA	control element assembly
CETOP-D	off-line DNB algorithm for safety analysis
CETOP-2	on-line DNB algorithm used in CPC
COLSS	core operating limit supervisory system
CPC	core protection calculator
DNB	departure from nucleate boiling
DNBR	DNB ratio
DNB-OPM	DNB over power margin
EOC	end of cycle
ESFAS	engineered safety features actuation system
Fq	three dimensional power peaking factor
Fxy	planar radial peaking factor
IOC	intermediate of cycle
LCO	limiting conditions for operation
LHR	linear heat rate (kW/ft)
LSSS	limiting safety system setting(s)
LPD	local power density
MOC	middle of cycle
MSCU	modified statistical combination of uncertainties
PDF	probability density function
PHPD	pseudo hot-pin power distribution
PSR	part strength rod (CEA)
RCS	reactor coolant system
RPS	reactor protection system
RSF	rod (CEA) shadowing factor
SAFDL	specified acceptable fuel design limits
SAM	shape annealing matrix
TSF	temperature shadowing factor

1. INTRODUCTION

1.1 Purpose

The purpose of this report is to describe Core Protection Calculator (CPC) setpoint analysis methodology for APR1400. The methodology is applied statistically by combining uncertainties involved in the determination of the Local Power Density (LPD) and Departure from Nucleate Boiling Ratio (DNBR) Limiting Safety System Settings (LSSS). CPC setpoint is determined by subtracting the overall uncertainty factors from the Safety Limit, but the overall uncertainty factors are cycle dependent. Therefore, the overall uncertainty factors analyzed in the methods presented in this report are applied in the CPC DNBR and LPD calculation for every cycle. The overall uncertainty factors assigned to LPD and DNBR, establish that the adjusted LPD and DNBR are conservative at 95/95 probability/confidence throughout the core cycle with respect to actual core conditions.

This report describes the statistical combination of state parameter and modeling uncertainty for the determination of the LSSS overall uncertainty factors.

The methods described here are the same as those reviewed and approved earlier for C-E System 80 plants in references 1&2.

1.2 Background

The plant protection system in operation on APR1400 is composed of two sub-systems:

1. Engineered Safety Features Actuation System (ESFAS)

2. Reactor Protection System (RPS)

The CPC initiates two of the ten trips in the Reactor Protection System, the low DNBR trip and the high local power density trip. The RPS assesses the LPD and DNBR LSSS as a function of monitored reactor plant parameters. The CPC uses these monitored parameters as input data and calculates the on-line LPD and DNBR margin to trip limits. A list of variables that affect the CPC calculation of LPD and DNBR(in terms of the LPD and DNBR LSSS) is given in Table 1-1.

These two protective functions assure safe operation of a reactor in accordance with the criteria established in 10 CFR 50 Appendix A (Criteria Number 10, 20, and 25). The LSSS, combined with the Limiting Conditions for Operation (LCO), establishes the thresholds for automatic protection system actions to prevent the reactor core from exceeding the Specified Acceptable Fuel Design Limits (SAFDL) on center line fuel melting and Departure from Nucleate Boiling (DNB).

1.3 Report Scope

The scope of this report encompasses the following objectives:

- Describe CPC setpoint analysis methods applied statistically to combine uncertainties.

- Evaluate the aggregate uncertainties as they are applied in the calculation of LPD and DNBR.

The probability density functions associated with the uncertainties defined in Section 2.1 are analyzed to obtain the LPD and DNBR overall uncertainty factors based on a 95/95 (probability/confidence) level tolerance limit. The methods used for the determination of uncertainty on the power measurement, the core average Axial Shape Index (ASI), and the hot-pin ASI are also described.

Appendices A and B provide the summary of the CPC LPD and DNBR setpoint calculation. And appendix C provides CPCS axial power distribution algorithm.

The methods presented in this report are applicable to APR1400.

Table 1-1 Variables Affecting the LPD and DNBR for CPC

LPD

1. Core Power Level
2. Axial Power Distribution
3. Radial Power Distribution
4. CEA Position

DNBR

1. Core Power Level
2. Axial Power Distribution
3. Radial Power Distribution
4. CEA Position
5. Core Coolant Inlet Temperature
6. Core Coolant Pressure
7. Primary Coolant Mass Flow

2. ANALYSIS

2.1. Analysis Techniques

2.1.1. Uncertainty Components

All uncertainty components considered in the determination of the overall uncertainty factors for the calculation of LPD and DNBR, are listed as below:

- Uncertainty in the ex-core detector signal measurement
- Uncertainty in the CEA position measurement
- Uncertainty in the temperature, pressure, and flow measurements
- Uncertainty in the CPC LPD calculation due to the CPC power distribution synthesis for the CPC LPD algorithm
- Uncertainty in the CPC DNB calculation due to the CPC power distribution synthesis for the CPC DNB algorithm
- Uncertainty in the CPC DNB algorithm with respect to the safety analysis DNB algorithm
- Uncertainty in the measurement of planar radial peaking factors using CECOR
- Computer processing uncertainty
- Rod (CEA) Shadowing Factor (RSF) uncertainty
- Shape Annealing Matrix (SAM) uncertainty
- Boundary Point Power Correlation Coefficient (BPPCC) uncertainty
- Fuel and poison rod bow uncertainty
- Axial fuel densification uncertainty
- Engineering factor due to manufacturing tolerance

2.1.2. General strategy

The reactor core simulator generates typical three-dimensional (3-D) core power distributions that reflect a variety of plant operating conditions. The uncertainty analyses are performed by comparing the 3-D peaking factor (Fq) and DNB-OPM (obtained from the reactor core simulator) to those calculated by the off-line CPC (tuned to the reactor core simulator through a simulation of the appropriate startup testing). Figures 2-1 and 2-2 show an overview of the uncertainty analysis process. Note that the overall DNB uncertainty factor is calculated in overpower margin (DNB-OPM) and not in DNBR units, because the uncertainty factor is used as a multiplier on heat flux in the on-line CPC DNBR calculation. The Fq and DNB-OPM modeling uncertainty is combined statistically with other uncertainty in calculating the overall CPC uncertainty factors for LPD and DNB-OPM. The uncertainty analysis described in this report also involves stochastic simulation of the state parameter measurement uncertainty for the LPD and DNB-OPM calculations. The neutronic and thermal-hydraulic input parameters modeled statistically, are given in Table 2-1.

Approximately twelve hundred (1200) cases of power distributions at each of three burnups (BOC, MOC, and EOC) are used in the determination of the overall uncertainty factors for the LPD and DNB-OPM. These cases are chosen to encompass steady state and quasi-steady state plant operating conditions throughout the cycle lifetime. Power distributions are generated by changing power levels (20-100%), CEA configurations (first two lead banks full in to full out, and PSR-90% inserted to full out), and xenon and iodine concentrations (equilibrium, load maneuver, or oscillation).

The power measurement adjustment terms used for the LPD and DNB-OPM calculations are obtained from the CPC core power synthesis error, the secondary calorimetric power measurement error, the secondary calorimetric power to the CPC power calibration allowance, and a thermal power transient offset. This error component accounts for the error in the CPC power calculation during design basis events. A detailed description of these uncertainty factors is given in section 2.2.3. The method used for the CPC calculation of the core average ASI and hot-pin ASI uncertainty is described in section 2.2.4.

2.1.3. LPD LSSS statistical methods

The reactor core simulator is used to generate the hot-pin power distribution, which serves as the basis for comparison in establishing the uncertainty factors documented in this report. The CPC synthesized Fq is compared with that of the reactor core simulator. Figure 2-1 illustrates the calculation sequence employed in the Fq modeling uncertainty analysis. The Fq modeling error (X_F^i) between the CPC synthesized Fq and the actual Fq is defined as:

TS

where ("SYN" Fq)^i and ("ACTUAL" Fq)^i are the CPC Fq and the reactor core simulator Fq for the i-th case. The Fq error is analyzed for each case at each time-in-life. Approximately 1200 cases are analyzed at each time-in-life (BOC, MOC, and EOC).

The mean Fq error ($\bar{X}_{FM}$) and the standard deviation (σ_{FM}) of the Fq error can be calculated using:

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Since the mean and standard deviation are estimated from the data, the one-sided tolerance limit can be constructed from the k factor. For normal distributions, the one-sided tolerance limit factor (k) accounts for the sampling variations in the mean ($\bar{X}_{FM}$) and the standard deviation (σ_{FM}). A normality test of the error distribution is performed by using the D-prime statistic value to justify the assumption of a normal distribution.

The $K_{95/95}$ factor for a normal distribution is calculated as:

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If the error distribution is normal, the upper and lower one-sided 95/95 tolerance limits are calculated using the following equations:

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where $\bar{X}$, σ, and $k_{95/95}\sigma$ are the sample mean, standard deviation, and one-sided tolerance limit factor, respectively.

If the error is not normally distributed, one-sided 95/95 tolerance limits are calculated using non-parametric techniques based on order statistics and the binomial probability distribution. First, the error distribution is placed in order from the smallest to the largest value. The binomial distribution is used to calculate a locator, L, from the ordered error distribution which estimates the one-sided tolerance limit at a 95/95 probability/confidence level. The locator L is calculated using the following equation.

TS

The one-sided (upper or lower) 95/95 tolerance limit is obtained by selecting the error value (from the ordered error distribution) corresponding to the locator L. A non-parametric "kσ" is calculated from equation (2-4) using the determined one-sided tolerance limit and the known mean error.

2.1.4. DNBR LSSS statistical methods

The three-dimensional reactor core simulator provides a hot-pin power distribution for its DNB-OPM calculation and the corresponding ex-core detector signals for the CPC power distribution algorithm. In the reactor core simulator, the DNB-OPM calculation is performed by CETOP-D. A flowchart representing the reactor core simulator DNB-OPM calculation is shown in Figure 2-2.

The Reactor Coolant System (RCS) input temperature, pressure, and flow rate are randomly sampled from a uniform distribution within the respective operating ranges for both the reactor core simulator and CPC. In addition, for CPC, the measurement error of each of these state parameters is randomly sampled, then added to the selected state parameters. Operating ranges and measurement uncertainties of the state parameters performed for SKN Unit 3&4 cycle 1 are given in Table 2-2.

Thus, the effects of the error components associated with the temperature, pressure, and flow measurements, and the on-line to off-line DNB algorithm, are accounted for in the determination of the CPC DNB-OPM modeling error via the MSCU program.

The CPC DNB-OPM modeling error (with MSCU) is defined as: **TS**

where ("SYN" DNB-OPM)^i and ("ACTUAL" DNB-OPM)^i represent the CPC DNB-OPM and the reactor core simulator DNB-OPM for the i-th case. The DNB-OPM errors are analyzed separately for each time-in-life. Each error distribution is tested for normality and the mean DNB-OPM error ($\overline{X}_D$), standard deviation (σ_D), and one-sided upper 95/95 tolerance limit, are then computed.

2.2 Analyses Performed

2.2.1 LPD LSSS Uncertainty Analysis

2.2.1.1 Power Distribution Synthesis Uncertainty

The reactor core simulator calculates ex-core detector signals for the CPC power distribution synthesis. An error component for each ex-core signal is randomly selected from a standard normal error distribution and added to the ex-core signal. An error component of each Control Element Assembly (CEA) bank measurement (reed switch position transmitters) is obtained by randomly sampling from a uniform error distribution. The CEA position error component is then added to its respective CEA bank position. The CPC synthesizes a Pseudo Hot-pin Power Distribution (PHPD) by using (as input) the adjusted ex-core detector signals and the adjusted CEA bank positions. The CPC hot-pin power distributions are obtained using a cubic spline fitting technique in conjunction with constants such as planar radial peaking factors (Fxy), Rod Shadowing Factors (RSF), Boundary Point Power Correlation Coefficients (BPPCC), and Shape Annealing Matrix (SAM). A Temperature Shadowing Factor (TSF) correction is used in the CPC to account for the inlet temperature effect on the neutron flux power.

By comparing the reactor core simulator calculated Fq with the CPC synthesized Fq for each case, the Fq modeling error defined in equation (2-1) is obtained. By analyzing the Fq modeling errors, the CPC modeling error distributions (histogram) of Fq are obtained for each time-in-life. The mean Fq error ($\overline{X}_{FM}$), the standard deviation (σ_{FM}), and the lower 95/95 tolerance limit (TL_F) for the Fq modeling uncertainty are obtained by analyzing the error distribution at each time-in-life. The CPC Fq modeling error includes the uncertainty associated with the CPC power synthesis algorithm, the ex-core detector signal measurement, and the CEA position measurement.

2.2.1.2 CECOR Fxy Measurement Uncertainty

In the calculation of the CPC Fq modeling uncertainty, the CPC uses predicted values of Fxy. The Fxy values used by CPC are verified by the CECOR measured Fxy values during startup testing. Therefore, the CECOR Fxy measurement uncertainty which accounts for the differences between the CECOR Fxy and the actual Fxy is combined statistically with the Fq modeling uncertainty to obtain a net conservative uncertainty for Fq.

In the MSCU methodology, the Fxy uncertainty is simulated stochastically from the Fxy uncertainty Probability Density Function (PDF). Thus, the Fxy uncertainty is inherently applied within the state parameter stochastic simulation modeling uncertainty.

2.2.1.3 Rod (CEA) Shadowing Factor (RSF)

The CPC RSF constants used in the power synthesis algorithm are verified during startup testing. The predicted RSF values are calculated by simulating the RSF test and then analyzing the ex-core detector response for various CEA configurations.

In the MSCU methodology, the RSF uncertainty is randomly selected from a uniformly uncertainty distribution. This uncertainty is then multiplied to the RSF generated by the reactor core simulator and then used as input to the CPC power distribution algorithm.

2.2.1.4 Shape Annealing Matrix (SAM)

The CPC Shape Annealing Matrix (SAM) elements used in the power synthesis algorithm are verified during power ascension testing. The predicted SAM elements are calculated by simulating a free unrodded xenon oscillation similar to SAM startup test measurement procedure. The predicted SAM elements are then determined from a regression analysis of the ex-core signals and the corresponding bottom, middle and top third integrals of the core peripheral power.

In the MSCU methodology, the Barrel of SAMs is applied as SAM uncertainty. The Barrel of SAMs is a family of SAMs calculated with noisy ex-core signal and peripheral powers.

2.2.1.5 Boundary Point Power Correlation Coefficient (BPPCC)

The CPC Boundary Point Power Correlation Coefficient (BPPCC) values used in the power synthesis algorithm are verified during power ascension testing. The predicted BPPCC values are calculated by simulating a free unrodded xenon oscillation similar to the SAM measurement procedure. The predicted BPPCC values are then determined from a regression analysis of the top and bottom one-third, of the core average power integrals and the boundary point powers at the top and bottom of the core.

In the MSCU methodology, the BPPCC uncertainty is randomly selected from a uniformly uncertainty distribution. This uncertainty is then multiplied to the BPPCC generated by the reactor core simulator then used as input to the CPC power distribution algorithm.

2.2.1.6 Other Uncertainty Factors

<u>Axial Fuel Densification Uncertainty</u>

The axial fuel densification uncertainty factor considers the global effect of the shrinkage (due to heating and irradiation) of the fuel pellet stack, on Fq, because the CPC Fq calculation does not account for it directly. This uncertainty factor, calculated based on the methodology described in Reference 3, will be used as a multiplier on the net Fq uncertainty.

<u>Fuel and Poison Rod Bow Uncertainties</u>

The fuel and poison rod bow uncertainty considers the effect of "bowing" of the fuel and poison rods, due to heating and irradiation, on Fq, because the CPC Fq calculation does not account for it directly. These factors, calculated based on the methodology described in Reference 4, will be part of the composite Fq modeling uncertainty.

<u>Computer Processing Uncertainty</u>

The computer processing uncertainty considers the effect of the computer machine precision of the off-line computer and the on-site computer on the CPC Fq calculations. The computer processing uncertainty will be part of the composite Fq modeling uncertainty.

<u>Engineering Factor Uncertainty</u>

The engineering factor uncertainty accounts for the effect of variations in the fuel pellet and clad manufacturing process. Variations in fuel pellet diameter and enrichment are included in this allowance, as are variations in clad diameter and thickness. These result in variations in the quantity of fissile material and introduce variations in the gap conductance. This factor, calculated based on methodology described in Reference 3, will be part of the composite Fq modeling uncertainty.

2.2.1.7 Overall LPD LSSS Uncertainty Factor

An overall CPC Fq uncertainty factor is determined by combining 95/95 probability/confidence tolerance limits of the error components. This overall uncertainty factor includes Fq modeling uncertainty, CECOR Fxy measurement uncertainty, startup test acceptance criteria uncertainty, axial fuel densification uncertainty fuel and poison rod bow uncertainties, computer processing uncertainty, engineering factor uncertainty and reactor core simulator modeling uncertainty. Figure 2-3 shows the calculation sequence to determine an overall LPD LSSS uncertainty factor.

The Fq modeling error (X^{i}_{FM}) defined in equation (2-1) can be rewritten as: TS

The "kσ" of the composite Fq modeling uncertainty is determined by combining the "kσ" for CPC power distribution synthesis ($k\sigma_{FM}$), engineering factor ($k\sigma_{FE}$), rod bow penalties ($k\sigma_{FF}$, $k\sigma_{PP}$) and computer processing ($k\sigma_{CP}$). This ($k\sigma_{FM}$) is calculated using the root-sum-square technique: TS

The resultant composite Fq modeling penalty factor (PM_F) is determined using the lower 95/95 composite tolerance limit for Fq (TL_F) as follows: TS

The lower tolerance limit is used to assure conservative CPC Fq calculations at a 95/95 probability and confidence level.

The last step in determining an overall Fq uncertainty factor (BERR3) is to combine the composite modeling uncertainty (PM_F) and the axial fuel densification uncertainty (PA). Consequently, TS

The LSSS LPD overall uncertainty factor (BERR3) is used as a multiplier in the CPC calculated LPD (KW/FT) such that: TS

Use of the overall uncertainty factor (BERR3) for the CPC calculated LPD assures at least a 95% probability, at a 95% confidence level, that the CPC LPD will be larger than the "ACTUAL" LPD.

2.2.2 DNBR LSSS Uncertainty Analysis

2.2.2.1 System Parameter Uncertainties

In order to determine the minimum DNBR (MDNBR) limit, thermal margin methods utilize the detailed TORC code with the KCE-1 DNB correlation. The MDNBR for the LSSS includes the uncertainty associated with system parameters that describe the physical system. These system parameters include such as reactor core geometry, pin-by-pin radial power distributions, and inlet and exit flow boundary conditions. To combine the sources of system parameter uncertainty, the following factors are combined statistically in the MDNBR limit:

1. Core inlet flow distribution
2. Engineering factor on enthalpy rise
3. Systematic fuel rod pitch
4. Systematic fuel rod diameter
5. Engineering factor on heat flux
6. KCE-1 CHF correlation
7. KCE-1 CHF correlation cross validation penalty
8. T-H code uncertainty penalty

These uncertainties are combined statistically to yield the DNBR pdf. The MSCU MDNBR limit provides, at a 95/95 probability and confidence level, that the limiting fuel pin will avoid DNB. Since the MSCU MDNBR limit includes system parameter uncertainty, this uncertainty is not considered again in the determination of the CPC DNB-OPM overall uncertainty factor.

In the MSCU methodology, DNBR limits are sampled from the DNBR pdf itself. Thus, both the system and state parameter uncertainties are combined statistically in the CPC overall uncertainty factors. Figure 2-3 provides a schematic of the MSCU methodology.

2.2.2.2 State Parameter Measurement Uncertainty

The on-line DNB algorithm used for CPC requires primary system pressure, core inlet temperature, core power, primary coolant flow rate, and hot-pin power distribution as input. Since pressure, temperature, and flow affect the calculation of DNBR, errors associated with these state parameters must be accounted for in the CPC DNB-OPM uncertainty analysis. In the MSCU program, the thermal-hydraulic generator (Figure 2-2) stochastically selects the RCS pressure, RCS inlet temperature, and RCS flow. The state parameters are randomly selected within their operating ranges. The state parameter error components are also randomly selected from an error distribution, then added to the respective state parameters. This procedure allows direct simulation of the effects of the CPC on-line inlet temperature, pressure, and flow measurement, and of their respective contributions to uncertainty on the CPC DNB-OPM overall uncertainty. Therefore, uncertainty related to temperature, pressure, and flow are implicitly accounted for in the DNB-OPM modeling uncertainty.

2.2.2.3 DNB-OPM Modeling Uncertainty with MSCU

The CPC DNB-OPM modeling uncertainty with MSCU is made up of uncertainty associated with the techniques used for power distribution synthesis, DNB algorithm, ex-core detector signal measurement, CEA position measurement, RCS inlet temperature measurement, RCS pressure measurement, and RCS flow measurement. In order to include the RCS inlet temperature, pressure, and flow rate effects in the DNB-OPM modeling uncertainty, a stochastic simulation program is employed. The MSCU program stochastically simulates the measurement uncertainties and operating ranges associated with RCS state parameters along with the DNB-OPM error component associated with the on-line to off-line DNB algorithms.

By comparing the reactor core simulator calculated DNB-OPM with the CPC calculated DNB-OPM for each case, the DNB-OPM modeling error is obtained. The mean of the DNB-OPM modeling error is represented by:

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The DNB-OPM errors are analyzed separately for each time-in-life. Each error distribution is tested for normality and then the mean DNB-OPM error ($\overline{X}_{DM}$), standard deviation (σ_{DM}), and one-sided upper 95/95 tolerance limit are computed.

In the MSCU, the secondary calorimetric power error and neutron power synthesis error are included in the DNB-OPM modeling error instead of in the power measurement uncertainty. A detailed description of these uncertainty factors is given in section 2.2.3.

2.2.2.4 Other Uncertainty Factors

<u>DNBR Computer Processing Uncertainty</u>

The computer processing uncertainty considers the effect of the off-line to the on-line computer machine precision on the CPC DNBR calculations. The computer processing uncertainty is represented by the term $(k\sigma)_{CP}$ and is part of the DNB-OPM composite modeling uncertainty $(k\sigma)_{DT}$. This computer processing uncertainty $(k\sigma)_{CP}$ is calculated using the following equation:

TS

<u>Fuel and Poison Rod Bow Uncertainties</u>The fuel and poison rod bow uncertainties for DNB-OPM are determined by the method described in Section 2.2.1.6.

2.2.2.5 Overall DNBR LSSS Uncertainty Factor

The off-line overall CPC uncertainty factor for DNB-OPM (BERR1) is determined by combining all one-sided (upper) 95/95 probability/confidence tolerance limits of the error components. This overall uncertainty factor includes a DNB-OPM modeling uncertainty, a CECOR Fxy measurement uncertainty, a computer processing uncertainty and fuel and poison rod bow uncertainties. Figure 2-3 illustrates the calculation sequence used to determine the overall DNB-OPM uncertainty factor.

The mean error for DNB-OPM modeling uncertainty is $\overline{X}_{DM}$.

The composite ($k\sigma_{DT}$) is made up of uncertainty associated with the DNB-OPM modeling algorithm ($k\sigma_{DM}$), rod and poison bow penalties ($k\sigma_{PF}$, $k\sigma_{PP}$) and DNBR computer processing ($k\sigma_{CP}$). Using the root-sum-square technique, this composite $(k\sigma)_{DT}$, is calculated as:

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The upper 95/95 composite modeling tolerance limit for DNB-OPM (TL_D) is used for conservative CPC DNB-OPM calculations and determined by:

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The composite DNB-OPM modeling penalty factor (PM_D) can then be determined using:

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An overall DNB-OPM uncertainty factor for CPC (BERR1) is determined using:

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Use of the overall uncertainty factor (BERR1) for the off-line CPC calculated DNB-OPM assures at least a 95% probability, at a 95% confidence level, that the "ACTUAL" DNB-OPM will be larger than the CPC DNB-OPM:

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Therefore, the use of the overall uncertainty factor (BERR1) as a multiplier for the on-line CPC hot pin heat flux distribution used in the DNBR calculation assures for at least the 95% probability, at a 95% confidence level, that the CPC calculated DNBR will be less than the actual core minimum DNBR:

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[CPC calculated hot pin DNBR corrected with $(BERR1)_{95/95}$ < actual core minimum DNBR (2-20)]

2.2.3 Core Power Level Measurement Uncertainty

2.2.3.1 Uncertainty Components

The CPC utilizes two different calculations of core power, thermal power and neutron flux power, for the LPD and DNBR calculation. The CPC thermal power is calculated based on the reactor coolant temperature and the reactor coolant mass flow rate. The CPC thermal power measurement errors is calculated by deterministically combining the secondary calorimetric power measurement error, the secondary calorimetric power to CPC power calibration allowance, and the thermal power transient offset.

The CPC neutron flux power is calculated based on the sum of the tri-level ex-core detector signals. The CPC neutron flux power measurement error is calculated from the CPC neutron flux power synthesis error, the secondary calorimetric power measurement error, and the secondary calorimetric power to the CPC power calibration allowance.

Secondary Calorimetric Power Measurement Error

Both COLSS and CPC use secondary calorimetric power as a measure of true core power for their LHR/LPD and DNBR calculations. The calculation of secondary calorimetric power has an uncertainty associated with it.

The secondary calorimetric power measurement error (X_{SC}) consists of the uncertainty components for the following parameters:

1. Feedwater Flow
2. Feedwater Temperature
3. Secondary System Pressure
4. Pressurizer Heaters
5. Reactor Coolant System Loss
6. Coolant Pump Heat
7. Component Cooling Water

The result of a typical analysis of the secondary calorimetric power error, based on the above uncertainty components and secondary instrument accuracies, is provided in Figure 2-4. Verification of the secondary calorimetric power error is performed during startup testing.

The secondary calorimetric power measurement error is conservatively bounded by the following core power error function (X_{SC}):

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In the MSCU program, this uncertainty is applied as an additive penalty directly on the core power used in the COLSS and on the thermal and neutron flux power used in CPC. This uncertainty is implemented as a function of core power in both COLSS and CPC, but only for DNB calculations greater than 80% power, will the secondary calorimetric power measurement uncertainty be represented by a set of pdfs. The DNBR overall uncertainty analysis will be sampled statistically from these uncertainty pdfs. This uncertainty component will thus inherently be part of the DNBR overall uncertainty factors. The secondary calorimetric power measurement uncertainty is included in the DNBOPM overall uncertainty factors (BERR1) instead of in the power measurement uncertainty (BERR0, BERR2 in CPC).

Application of this uncertainty within the overall uncertainty analysis will continue to assure conservative DNBR POL results (at a 95/95 levels of probability and confidence) when CPC uses calculations by COLSS and DNBR

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Neutron Flux Power Synthesis Error

The neutron flux power synthesis error (X_{NF}) is obtained by comparing the CPC synthesized neutron flux power level to the reactor core simulator power for 1200 cases at each time-in-life. The CPC neutron flux power calculation is based on ex-core detector signals, and includes a neutron flux power measurement uncertainty. One component of this uncertainty is the power synthesis uncertainty. The most non-conservative value of the one-sided tolerance limit at a 95/95 probability/confidence level is used at each power level.

However, the MSCU methodology applies this uncertainty within the calculation of the CPC DNBR overall uncertainty factor instead of including it in the separate CPC power measurement uncertainty factor.

In the MSCU analysis, the power synthesis uncertainty is applied on a case-by-case basis within the CPC DNBR overall uncertainty calculation. This uncertainty is inherently part of the DNBR overall uncertainty factor.

Application of this uncertainty within the overall uncertainty analysis will continue to assure a conservative DNBR calculation by CPC at a 95/95 probability/confidence level.

2.2.3.2 Uncertainty Biases for DNBR Calculation

Figure 2-5 shows how BERRi constants are actually used in the DNBR and LPD calculations. The uncertainty biases for power used in the DNBR calculation are added to the calculated power level :

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The thermal power measurement uncertainty constant for the CPC DNBR calculation (BERR0) is determined by selecting the maximum value of the thermal power measurement errors (X_{CA}+X_{TD}) for the core power range (0-100% full power). This uncertainty factor (BERR0) is applied as an additive bias to the CPC thermal power.

The neutron flux power measurement uncertainty constant for the CPC DNBR calculation (BERR2) is determined by selecting the maximum neutron flux power measurement error (X_{CA}+X_{ND}) at each power level for the core power range (0-130% full power). This uncertainty factor (BERR2) is applied as an additive bias to the CPC neutron flux power.

For the DNBR calculation, the CPC selects the larger of the thermal power ($POWER_{TH}$) or the neutron flux power ($POWER_{NF}$).

2.2.3.3 Uncertainty Biases for LPD Calculation

Figure 2-5 shows how BERRi constants are actually used in the DNBR and LPD calculations. The uncertainty biases for power used in the LPD calculation are added to the uncorrected power level:

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The core power measurement uncertainty factor for the LPD calculation (BERR4) is obtained by selecting the largest of the CPC thermal power error (X_{CA}+X_{TF}) or the CPC neutron flux power errors (X_{CA}+X_{NF}+X_{TF}) over the core power range from 0-130% full power. For the LPD calculation, the CPC selects the largest of the thermal power or the neutron flux power. Next, the uncertainty constant (BERR4) and the power level dependent error (X_{SC}) are applied as an additive bias to the selected power.

2.2.4 Axial Shape Index Uncertainty

The axial shape index (ASI) for the core average and the hot-pin power distributions is computed from the power generated in the lower and upper halves of the core:

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The ASI error is defined by:

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The core average and hot-pin ASI uncertainty analyses are performed by comparing the CPC synthesized ASI and the reactor core simulator ASI. The resulting error distributions are analyzed to obtain the upper and lower 95/95 tolerance limits. The hot-pin ASI and the core average ASI uncertainties performed for SKN Unit 3&4 cycle 1 are presented in Tables 2-3 and 2-4.

2.2.5 DNBR Uncertainty for Mixed Cores

In the mixed cores, the DNBR uncertainty is calculated for two fuel types respectively. The larger value between the two DNBR uncertainties is selected and installed in the CPC for conservatism. In addition, the DNBR penalty factor for the mixed cores resulting from the type of CHF correlation is added to the DNBR uncertainty. Because, in the CPC algorithm, there is only one type of CHF correlation, i.e. CE-1 type correlation, the correlation coefficient of the new fuel is installed in the CPC in mixed cores. Therefore, the DNBR thermal margin decrement of existing fuel compared to new fuel is considered as the DNBR penalty factor for mixed cores. The DNBR penalty factor is defined as the following equation in case the existing fuel reaches the DNBR limit faster than the new fuel.

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where, Limiting Heat Flux is the heat flux corresponding to DNBR limit.

Table 2-1 Statistically Modeled Variables

NEUTRONICS
CEA Positions
Ex-Core Detector Signals
THERMAL-HYDRAULICS
RCS Pressure
Core Inlet Temperature
Core Flow

Table 2-2 Ranges and Measurement Uncertainties of Parameters

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Table 2-3 Hot-pin ASI Error[(1)] Analysis

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Table 2-4 Core Average ASI Error(1) Analysis

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Figure 2-1 CPC Simulation for Fq

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Figure 2-2 CPC Simulation for DNBR

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Figure 2-3 MSCU Schematic

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Figure 2-4 Secondary Calorimetric Power Error

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Figure 2-5 Application of BERRi Terms in CPC DNBR and LPD Calculations

3. RESULTS

The analysis techniques described in Section 2 were used to determine the uncertainty associated with the LPD and DNBR LSSS at 95/95 probability/confidence levels. Figure 2-5 shows applications of this uncertainty in CPC. These CPC –calculated DNBR and LPD are compared to DNBR and LPD setpoint.

The results of the analyses performed for SKN Unit 3&4 cycle 1 are presented in this section.

3.1 LPD LSSS

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3.2 DNBR LSSS

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Table 3-1 CPC Synthesized Fq Modeling Error(1) Analysis

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Table 3-2 CPC Synthesized DNB-OPM Modeling Error(1) Analysis

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Table 3-3 Contribution of Individual Uncertainties to CPC Overall Uncertainty Factors

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4. REFERENCES

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2. CEN-356(V)-P-A, “Modified Statistical Combination of Uncertainties,” Rev.1-P-A, Combustion Engineering, Inc., May 1988.

3. CENPD-139-P, "Fuel Evaluation Model,” Combustion Engineering, Inc., October 1974.

4. CENPD-225-P-A, “Fuel and Poison Rod Bowing,” Combustion Engineering, Inc., June 1983.

APPENDIX A CPC LPD SETPOINT CALCULATION

CPC LPD Setpoint (LSSS) = Safety Limit for LPD - Overall Uncertainty Factor (BERR3, BERR4)

CPC LPD Setpoint (LSSS) – LPD calculated by CPC = Margin

Safety Limit for LPD - (LPD calculated by CPC + Overall Uncertainty Factor (BERR3, BERR4)) = Margin

1. CPC LPD overall uncertainty factor (BERR3)

(1) Composite Fq modeling penalty factor (PM_F)

1) The mean of the composite Fq modeling uncertainty ($\bar{X}_{FM}$)

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2) kσ of the composite Fq modeling uncertainty $(k\sigma)_{FT}$

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(2) Axial fuel densification uncertainty (PA)

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2. Core power measurement uncertainty factor (BERR4)

(1) Neutron flux power synthesis error

(2) Calibration Allowance

(3) Secondary Calorimetric Power Measurement Error

(4) Thermal and Neutron Flux Power Transient Offset for LPD

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APPENDIX B CPC DNBR SETPOINT CALCULATION

CPC DNBR Setpoint (LSSS) = Safety Limit for DNBR - Overall Uncertainty Factor(BERR0,BERR1,BERR2)

CPC DNBR Setpoint (LSSS) – DNBR calculated by CPC = Margin

Safety Limit for DNBR - (DNBR calculated by CPC + Overall Uncertainty Factor (BERR0,BERR1,BERR2)) = Margin

1. CPC DNB-OPM uncertainty factor (BERR1)

(1) The composite DNB-OPM modeling penalty factor (PM_D)

1) The mean of the DNB-OPM modeling error ($\bar{X}_{DM}$)

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2) kσ of the composite Fq modeling uncertainty $(k\sigma)_{DT}$

A. DNB-OPM modeling algorithm uncertainties ($k\sigma_{DM}$)

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B. rod and poison bow penalties ($k\sigma_{PF}$, $k\sigma_{PP}$)

C. DNBR computer processing ($k\sigma_{CP}$)

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2. Thermal power measurement uncertainty factor for the CPC DNBR calculation (BERR0)

(1) Calibration Allowance

(2) Thermal Power Transient Offset

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3. Neutron flux power measurement uncertainty factor for the CPC DNBR calculation (BERR2)

(1) Calibration Allowance

(2) Neutron Flux Power Transient Offset

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APPENDIX C CPCS AXIAL POWER DISTRIBUTION ALGORITHM

The CPCS axial power distribution algorithm uses the measured SAM and BPPCC constants which are determined during the startup test at the site. The SAM and BPPCC constants are determined by using the least square fitting of startup test data, and are used for the whole cycle. Therefore, the SAM and BPPCC constants are cycle-dependent, but they are not burnup-dependent. They are installed using the plant measured data, and thus, further verification is not needed.

The SAM and BPPCC constants are determined by using the power distributions measured during power ascension testing in the BOC. So, the error in axial power distribution may be generated when the axial shapes are different from those of BOC such as flat, saddle, top or bottom peak axial shapes. This error is taken into account in Overall Uncertainty Factor by overall uncertainty analysis.

In overall uncertainty analysis, CPCS calculates the axial power distributions using the SAM and BPPCC constants which are simulated in the BOC for the 4,800 core conditions generated by reactor core simulator. Various power distribution (flat, saddle, top or bottom peak and so on) in table-C1 are used in the determination of the overall uncertainty factors for LPD and DNB-OPM. Therefore, the difference in axial shapes between reactor core simulator and CPCS are considered statistically in Overall Uncertainty Factor.

Table C-1 Core Conditions of Axial Power Distribution for Overall Uncertainty Analysis **TS**