San Onofre Nuclear Generating Station
Units 2 and 3

CEN-283(S)-NP

STATISTICAL COMBINATION OF UNCERTAINTIES

PART III

Uncertainty Analysis of Limiting Conditions for Operation
San Onofre Nuclear Generating Station
Units 2 and 3

REACTOR DESIGN
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ABSTRACT

Part III of the Statistical Combination of Uncertainties (SCU) report describes the methodology for statistically combining uncertainties that are involved in the determination of the Limiting Conditions for Operation (LCO) on the Linear Heat Rate (LHR) and Departure from Nucleate Boiling Ratio (DNBR) for San Onofre Nuclear Generating Station (SONGS) Units 2 and 3. The overall uncertainty factors assigned to LHR and DNB Overpower Margin (DNB-OPM) establish that the adjusted LHR and DNB-OPM are conservative at a 95/95 probability/confidence level throughout the core cycle with respect to core conditions.

The Statistical Combination of Uncertainties report describes a method for statistically combining uncertainties. Part I of this report describes the statistical combination of system parameter uncertainties in thermal margin analyses. Part II of this report describes the statistical combination of state parameter uncertainties for the determination of the LSSS overall uncertainty factors. Part III of this report describes the statistical combination of state parameter and modeling uncertainties for the determination of the LCO overall uncertainty factors.

The methods described here (Part III) are the same as those reviewed and approved for C-E System 80 plants.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

DEFINITION OF ABBREVIATIONS

ASI	Axial Shape Index
APHPD	Axial Pseudo Hot-Pin Power Distribution
BOC	Beginning of Cycle
CDF	Cumulative Distribution Function
C-E	Combustion Engineering
CEA	Control Element Assembly
CETOP	C-E Thermal On-Line Program
CETOP-D	Off-Line DNB Algorithm for Safety Analysis
CETOP-1	DNB Algorithm Used in COLSS (on-line) and Core Simulator (off-line)
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 Overpower Margin
EOC	End of Cycle
ESFAS	Engineered Safety Features Actuation System
Fq	Three-Dimensional Power Peaking Factor
Fxy	Planar Radial Power Peaking Factor
LCO	Limiting Conditions for Operation
LHR	Linear Heat Rate (kw/ft)
LOCA	Loss of Coolant Accident
LSSS	Limiting Safety System Setting(s)
MOC	Middle of Cycle
NSSS	Nuclear Steam Supply System
PDF	Probability Distribution Function
PHPD	Pseudo Hot-Pin Power Distribution
PLR	Part Length Rod (CEA)
POL	Power Operating Limit
RCS	Reactor Coolant System
RPS	Reactor Protection System
SAFDL	Specified Acceptable Fuel Design Limits
SCU	Statistical Combination of Uncertainties

1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this report is to describe the methodology for statistically combining uncertainties associated with the LHR and DNBR LCO[1]. All uncertainty components considered in the determination of the overall uncertainty factors for the core Power Operating Limits (POL) based on the LHR and DNBR calculations are listed as follows:

1. Uncertainty in the in-core detector signal measurement
2. Uncertainty in the Control Element Assembly (CEA) position measurement
3. Uncertainties in the temperature, pressure, and flow measurements
4. Uncertainty in the measurement of planar radial peaking factors (Fxy) using CECOR[2]
5. Uncertainty in the Core Operating Limit Supervisory System (COLSS) LHR calculation due to the COLSS power distribution synthesis.
6. Uncertainty in the COLSS DNB-OPM calculation due to the COLSS power distribution synthesis for COLSS DNB algorithm
7. Uncertainty in the COLSS DNB algorithm with respect to the safety analysis DNB algorithm
8. Computer processing uncertainty
9. Fuel and poison rod bow uncertainties
10. Axial fuel densification uncertainty
11. Engineering factor due to manufacturing tolerance

1.2 BACKGROUND

The COLSS is a digital computer monitoring system. The purpose of COLSS is to assist the operator in maintaining specified operating limits during normal operation. The principal function of COLSS is to aid the operator in monitoring the limiting conditions for operation based on DNBR margin, LHR, azimuthal tilt, and maintaining core power at or below licensed power. COLSS results are presented to the operator via control room outputs such as alarms, meters, CRT displays, and printer reports.

Operation of the reactor core within these limits assures that no anticipated operational occurrence will result in exceeding the Specified Acceptable Fuel Design Limits (SAFDL) on DNBR and centerline fuel melting. In addition, the consequences of postulated accidents such as a LOCA will be acceptable with respect to applicable criteria. A list of variables affecting DNBR and LHR operating limits and monitored NSSS variables is given in Table 1-1.

The functional relationship between the monitoring systems (COLSS)[1] and the safety systems (CPC)[3] is as follows: Monitoring systems aid the operator during normal operation in maintaining the plant within established operating limits. On the other hand, safety systems are designed to minimize the probability and magnitude of release of radioactivity to the environment during abnormal operation. The integrated functions of the monitoring and protective systems via the plant technical specifications assure that all safety requirements are satisfied[4]. More detailed discussions of these systems may be found in References 1 and 3.

A generic SCU method for C-E System 80 plants has been applied and licensed for Palo Verde unit 1. The SCU methodology described in this report is the same as the methodology used for C-E System 80 NSSS[5-7].

The SCU method is applied to determine overall uncertainty factors for the LHR and DNBR operating limits. The overall uncertainty factors assigned to LHR and DNB-OPM establish that the adjusted LHR and DNB-OPM will be conservative throughout the core cycle with respect to actual core conditions.

1.3 REPORT SCOPE

The objectives of this report are:

1. to describe the methods used for statistically combining uncertainties applicable to the LHR and DNBR LCO;
2. to evaluate the aggregate uncertainties as they are applied in the calculation of the LHR and DNBR LCO.

The probability distribution functions associated with the uncertainties defined in Section 1.1 are analyzed to obtain the LHR and DNB-OPM overall uncertainty factors based on a 95/95 probability/confidence tolerance limit. The method used for the determination of the uncertainties on the core average Axial Shape Index (ASI) is also described. The methods presented in this report are applicable specifically to SONGS Units 2 and 3.

1.4 SUMMARY OF RESULTS

The analysis techniques described in Section 2.0 were applied to SONGS Unit 2 cycle 2. Using the stochastic simulation program, overall uncertainties for the LHR LCO and the DNBR LCO of [ ] and [ ], respectively, were calculated at a 95/95 probability/confidence level.

TABLE 1-1

VARIABLES AFFECTING LHR AND DNBR LCO
AND MONITORED NSSS VARIABLES

NSSS VARIABLES	MONITORED VARIABLE(S) INFERRED FROM:
Core Average Power	Turbine First Stage Pressure Cold Leg Temperature Hot Leg Temperature Feedwater Flow Steam Flow Feedwater Temperature Steam Pressure Reactor Coolant Pump Head Reactor Coolant Pump Speed Pressurizer Pressure
Radial Peaking Factor	CEA Positions Cold Leg Temperature
Azimuthal Tilt Magnitude	In-Core Neutron Flux
Normalized Axial Power Distribution	In-Core Neutron Flux CEA Group Positions
Reactor Coolant System Mass Flow	Reactor Coolant Pump Head Reactor Coolant Pump Speed Cold Leg Temperature Pressurizer Pressure
Reactor Coolant System Pressure	Pressurizer Pressure
Reactor Coolant Inlet Temperature	Cold Leg Temperature

2.0 ANALYSIS

2.1 GENERAL

The following sections describe the impact of the uncertainty components on the system parameters, the state parameters, and the COLSS modeling that affect the LHR and DNBR LCO. The effects of all individual uncertainties on the LCO overall uncertainty factors for LHR and DNBR are also discussed. In addition, this chapter presents the analyses performed to determine the overall uncertainty factors. These uncertainty factors when applied to the COLSS calculations of the LHR and DNB-OPM ensure at a 95/95 probability/ confidence level that the calculations are conservative.

2.2 OBJECTIVES OF ANALYSIS

The objectives of the analysis reported herein are:

1. to document the stochastic simulation technique used in the overall uncertainty analysis associated with the LHR and DNBR LCO and,
2. to determine LHR and DNB-OPM overall uncertainty factors, on the basis of a 95/95 probability/confidence level, so that the "adjusted" LHR and DNB-OPM (i.e., the COLSS synthesized value corrected by the respective uncertainty factor) will be conservative throughout the core cycle with respect to actual core conditions.

2.3 ANALYSIS TECHNIQUES

2.3.1 GENERAL STRATEGY

The uncertainty analyses are performed by comparing the three-dimensional power peaking factor (Fq) and DNB-OPM obtained from the reactor core simulator(3) to those calculated by COLSS (as 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. The reactor core simulator generates typical three-dimensional core power distributions which reflect a variety of operating conditions. Fq and DNB-OPM modeling uncertainties are statistically combined with other uncertainties in calculating overall uncertainty factors for the COLSS LHR and DNB-OPM calculations. The uncertainty analysis described in this report also includes the stochastic simulation of the state parameter measurement uncertainties for the LHR and DNB-OPM calculations[8]. The neutronic and thermal hydraulic input parameters that are statistically modeled are given in Table 2-1. A description of the individual measurement uncertainties is presented in Appendix A. The on-line to off-line thermal-hydraulic algorithm uncertainty section is also presented in Appendix A. The method used for the determination of the core average ASI uncertainty is described in Appendix B.

Approximately twelve hundred (1200) cases of power distributions at each of three burnups (BOC, MOC, EOC) are used in the determination of the overall uncertainty factors for the LHR and DNB-OPM calculations. The cases (total of 3600) considered herein 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, PLR-90% inserted to full out), and xenon and iodine concentrations (equilibrium, load maneuver, and oscillation).

2.3.2 LHR LCO 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 COLSS synthesized Fq is compared with that of the reactor core simulator. Figure 2-1 illustrates the calculational sequence employed in the Fq modeling uncertainty analysis. The Fq modeling error (X_F^i) between the COLSS synthesized Fq and the actual Fq is defined as:

$$X_F^i = \frac{(\text{"SYN" } F_q)^i}{(\text{"ACTUAL" } F_q)^i} - 1 \qquad (2\text{-}1)$$

where ("SYN" Fq)^i and ("ACTUAL" Fq)^i are the COLSS 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). Each error distribution is evaluated to obtain the mean Fq error ($\bar{X}_F$) and the standard deviation (σ_F).

The mean Fq error ($\bar{X}_F$) and the standard deviation (σ_F) of the Fq error can be calculated from:

$$\bar{X}_F = \frac{\sum_{i=1}^{N} X_F^i}{N} \tag{2-2}$$

$$\sigma_F = \left\{ \frac{\sum_{i=1}^{N} (X_F^i - \bar{X}_F)^2}{N-1} \right\}^{1/2} \tag{2-3}$$

where N = sample size

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 sample mean ($\bar{X}_F$) and the standard deviation (σ_F). A normality test of the error distribution is performed by using the D-prime statistic value[9-10] to justify the assumption of a normal distribution. If the error distribution is normal, the $k_{95/95}$ factor is calculated from an analytical expression[9-11] (see Section 2.3.2 of Part II). If the error is not normally distributed, a one-sided 95/95 tolerance limit is obtained by using non-parametric techniques [

]

2.3.3 DNB-OPM LCO STATISTICAL METHODS

The three-dimensional reactor core simulator provides a hot-pin power distribution for its DNB-OPM calculation and the corresponding in-core detector signals for the COLSS power distribution algorithm. In the reactor core simulator, the DNB-OPM calculation is performed with the simplified, relatively fast running DNB algorithm CETOP-1(13). [

]

A flowchart representing the reactor core simulator DNB-OPM calculation is shown in Figure 2-2.

The Reactor Coolant System (RCS) inlet temperature, pressure, and flow rate are [

] for both the reactor core simulator and COLSS. [

]

Operating ranges and measurement uncertainties of the LCO parameters are given in Table 2-2.

The COLSS DNB-OPM modeling error (with SCU) is defined as:

$$X_D^i = \frac{(\text{"SYN" DNB-OPM})^i}{(\text{"ACTUAL" DNB-OPM})^i} - 1 \qquad (2\text{-}4)$$

where ("SYN" DNB-OPM)^i and ("ACTUAL" DNB-OPM)^i represent the COLSS 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 analyzed for normal or non-parametric behavior to calculate the mean DNB-OPM error ($\bar{X}_D$), standard deviation (σ_D), and one-sided upper 95/95 tolerance limit.

2.4 ANALYSES PERFORMED

2.4.1 LHR LCO UNCERTAINTY ANALYSIS

2.4.1.1 POWER DISTRIBUTION SYNTHESIS UNCERTAINTY

The reactor core simulator calculates in-core detector signals for the COLSS power distribution synthesis. An error component for each in-core signal is [ ] and added to the in-core signal. An error component for each CEA bank position measurement (pulse counters) is obtained [ ] The CEA position error component is then added to its respective CEA bank position. The COLSS synthesizes a hot-pin power distribution by using (as input) the adjusted in-core detector signals and the adjusted CEA bank positions. A five element Fourier fitting technique is employed in COLSS to determine the core axial power shape.

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

2.4.1.2 CECOR Fxy MEASUREMENT UNCERTAINTY

In the calculation of the COLSS Fq modeling uncertainty, the COLSS uses predicted values of planar radial peaking factors (Fxy). The Fxy values used by COLSS are verified by the CECOR measured Fxy values during startup testing. Therefore, the CECOR Fxy measurement uncertainty[2] which accounts for the difference between the CECOR Fxy and the actual Fxy is combined with the Fq modeling uncertainty to obtain a net conservative uncertainty on Fq.

The CECOR Fxy error is defined as:

$$X_{FC}^{i} = \frac{G_i - P_i}{P_i} \qquad (2\text{-}5)$$

where P_i and G_i are the actual Fxy and the CECOR calculated Fxy for the i-th case, respectively.

2.4.1.3 OTHER UNCERTAINTY FACTORS

AXIAL FUEL DENSIFICATION UNCERTAINTY

The axial fuel densification uncertainty factor(16) considers the global effect of the shrinkage of the fuel pellet stack, due to heating and irradiation, on the Fq since the COLSS Fq calculation does not account for it directly. [

]

FUEL AND POISON ROD BOW UNCERTAINTIES

The fuel and poison rod bow uncertainties(17) consider the effect of "bowing" of the fuel and poison rods, due to heating and irradiation, on Fq since the COLSS Fq calculation does not account for it directly. The factors, calculated based on the methodology described in Reference 17, will be part of the composite COLSS Fq modeling uncertainty.

COMPUTER PROCESSING UNCERTAINTY

The computer processing uncertainty considers the effect of the computer machine precision of the C-E CDC-7600 computer and the on-site computer on the COLSS Fq calculations. The computer processing uncertainty will be part of the composite Fq modeling uncertainty.

ENGINEERING FACTOR UNCERTAINTY

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 variations in the gap conductance. This factor, calculated based on the methodology described in Reference 16, will be part of the composite Fq modeling uncertainty.

2.4.1.4 OVERALL LHR LCO UNCERTAINTY FACTOR

An overall COLSS Fq uncertainty factor is determined by combining all lower 95/95 probability/confidence tolerance limits of the error components. This overall uncertainty factor includes a Fq modeling uncertainty, a CECOR Fxy measurement uncertainty, a reactor core simulator modeling error, fuel and poison rod bow uncertainties, a computer processing uncertainty, an axial fuel densification uncertainty, and an engineering factor uncertainty. Figure 2-3 shows the calculation sequence to determine an overall LHR LCO uncertainty factor.

The COLSS Fq modeling uncertainty defined in equation (2-1) can be rewritten as:

$$X^i_{FM} = \frac{C_i - F_i}{F_i} \qquad (2\text{-}6)$$

where F_i and C_i are the reactor core simulator calculated Fq and the COLSS inferred value of Fq for the i-th case, respectively. A composite error (X^i_{FT}) of the Fq modeling uncertainty and the CECOR Fxy uncertainty can be deterministically calculated as follows:

$$X^i_{FT} = \frac{C_i}{F_i} * \frac{G_i}{P_i} - 1 \qquad (2\text{-}7)$$

By applying equation (2-5) and (2-6), this leads to:

$$X^i_{FT} = X^i_{FM} + X^i_{FC} + (X^i_{FM} * X^i_{FC}) \qquad (2\text{-}8)$$

The mean of the composite Fq modeling uncertainty can be then determined by:

$$\overline{X}_{FT} = \overline{X}_{FM} + \overline{X}_{FC} + (\overline{X}_{FM} * \overline{X}_{FC}) \qquad (2\text{-}9)$$

The composite $(k\sigma)_{FT}$ for the F_q modeling error is made up of uncertainties for COLSS power algorithm ($k\sigma_{FM}$), CECOR Fxy error ($k\sigma_{FC}$), rod bow penalties ($k\sigma_{PF}$, $k\sigma_{PP}$), computer processing ($k\sigma_{CP}$), and reactor core simulator[3] modeling error* ($k\sigma_{FR}$). By using the [ ] technique, this $(k\sigma)_{FT}$ is calculated by:

[ ] (2-10)

* See Appendix A (Section A.4)

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

$$PM_F = \frac{1}{1 + TL_F} \qquad (2\text{-}11)$$

where

$$TL_F = \overline{X}_{FT} - (k\sigma)_{FT} \qquad (2\text{-}12)$$

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

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

[ ] (2-13)

This LCO LHR overall uncertainty factor (UNCERT) is used as [ ] on the COLSS calculated LHR (KW/FT) such that:

$$\text{COLSS "SYN" LHR} * (\text{UNCERT})_{95/95} > \text{"ACTUAL" LHR} \qquad (2\text{-}14)$$

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

2.4.2 DNB-OPM LCO UNCERTAINTY ANALYSIS

2.4.2.1 DNB-OPM MODELING UNCERTAINTY WITH SCU

The COLSS DNB-OPM modeling uncertainty with SCU is made up of uncertainties associated with power distribution synthesis, in-core detector signal measurement, CEA position measurement, RCS 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 [ ] program is employed. The SCU program

[ ] the measurement uncertainties and operating ranges associated with RCS state parameters along with the on-line to off-line DNB algorithm error components.

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

[ ] (2-15)

[

]

2.4.2.2 OTHER UNCERTAINTY FACTORS

DNBR COMPUTER PROCESSING UNCERTAINTY

The computer processing uncertainty for the calculation of DNB-OPM considers the effect of the off-line (CDC 7600 computer) to the on-line computer machine precision on the COLSS DNB-OPM calculations. The computer processing uncertainty is represented by the terms of $(k\sigma)_{CP}$ 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:

[ ] (2-16)

where [

] defined in the following equation:

[ ] (2-17)

FUEL AND POISON ROD BOW UNCERTAINTIES

The fuel and poison rod bow uncertainties for DNB-OPM are determined by the same method described in Section 2.4.1.3.

SYSTEM PARAMETER UNCERTAINTIES

In order to determine the minimum DNBR (MDNBR) limit, C-E thermal margin methods utilize the detailed TORC code with the CE-1 DNBR correlation [14]. The MDNBR for the LCO includes the uncertainties associated with system parameters which describe the physical system. These system parameter uncertainties include: core geometry, pin-by-pin radial power distributions, inlet and exit flow boundary conditions, etc. In the statistical combination of system parameter uncertainties, the following uncertainties are combined statistically in the MDNBR limit:

1. Inlet flow distribution uncertainties
2. Fuel pellet density uncertainties
3. Fuel pellet enrichment uncertainties
4. Fuel pellet diameter uncertainties
5. Random and systematic uncertainties in fuel clad diameter
6. Random and systematic uncertainties in fuel rod pitch
7. DNB correlation uncertainties

The SCU MDNBR limit provides, at a 95/95 probability and confidence level, that the limiting fuel pin will avoid DNB. Since the SCU MDNBR limit includes system parameter uncertainties as described in Part I of this report, these uncertainties are implicitly included in the calculation of the COLSS DNB-OPM overall uncertainty factor.

2.4.2.3 OVERALL DNB-OPM LCO UNCERTAINTY FACTOR

The overall COLSS uncertainty factor for DNB-OPM (EPOL2) is determined by combining all one-sided (upper) 95/95 probability/confidence tolerance limits. This overall uncertainty factor includes a DNB-OPM modeling uncertainty, a CECOR Fxy measurement uncertainty, a reactor core simulator modeling error,a

DNBR computer processing uncertainty, and fuel and poison rod bow uncertainties. Figure 2-3 shows the calculational sequence used to determine the overall DNB-OPM uncertainty factor.

The composite DNB-OPM modeling uncertainty is obtained by following a similar strategy to that used for the Fq uncertainty analysis. The CECOR Fxy measurement uncertainty is calculated in terms of DNB-OPM units (using the sensitivity of DNB-OPM to Fxy {∂(%DNB-OPM)/∂(%Fxy)}). The mean value of the CECOR Fxy error is given by:

[ ] (2-18a)

and the CECOR F_{xy} "$k\sigma_{DC}$" is given by:

[ ] (2-18b)

The composite mean error of the composite DNB-OPM modeling uncertainty can then be obtained by:

$$\overline{X}_{DT} = \overline{X}_{DM} + \overline{X}_{DC} + (\overline{X}_{DM} * \overline{X}_{DC}) \quad (2\text{-}19)$$

The composite $(k\sigma)_{DT}$ is made up of uncertainties for the DNB-OPM modeling algorithm ($k\sigma_{DM}$), CECOR Fxy ($k\sigma_{DC}$), rod and poison bow penalties ($k\sigma_{PF}$, $k\sigma_{PP}$), DNBR computer processing uncertainty ($k\sigma_{CP}$), and a reactor core simulator modeling error ($k\sigma_{FR}$). Using [ ], this composite $(k\sigma)_{DT}$ is calculated as:

[ ] (2-20)

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

$$TL_D = \overline{X}_{DT} + (k\sigma)_{DT} \quad (2\text{-}21)$$

The penalty factor (PM_D) for this composite tolerance limit can be determined as:

$$PM_D = 1 + (TL)_D \qquad (2\text{-}22)$$

Therefore, the overall DNB-OPM uncertainty factor for COLSS (EPOL2) is:

[ ] (2-23)

This LCO DNB-OPM overall uncertainty factor (EPOL2) conservatively adjusts the COLSS calculated power operating limit such that:

COLSS "SYN" DNB-OPM *[ ] < "ACTUAL" DNB-OPM (2-24)

Use of the overall uncertainty factor (EPOL2) for the COLSS calculated DNB-OPM assures, at least a 95% probability, at a 95% confidence level, that the "ACTUAL" DNB-OPM will be larger than the COLSS DNB-OPM.

TABLE 2-1

STATISTICALLY MODELED VARIABLES

NEUTRONICS

CEA POSITIONS

IN-CORE SIGNALS

THERMAL HYDRAULICS

RCS PRESSURE

CORE INLET TEMPERATURE

CORE FLOW

TABLE 2-2

RANGES AND MEASUREMENT UNCERTAINTIES OF PARAMETERS

PARAMETERS	UNIT	RANGES	MEASUREMENT UNCERTAINTY
In-core Signal	(% power)		
CEA Position	(in)		
Core Inlet Coolant Temperature	(°F)		
Primary Coolant Pressure	(psia)		
Primary Coolant Mass Flow	(GPM)		

FIGURE 2-1

COLSS SIMULATION FOR Fq

FIGURE 2-2

COLSS SIMULATION FOR DNB-OPM

FIGURE 2-3

FLOWCHART FOR COLSS OVERALL UNCERTAINTIES
FOR LHR AND DNB-OPM

[ ]

3.0 RESULTS AND CONCLUSIONS

The analysis techniques described in Section 2 have been used to obtain uncertainties associated with the LHR and DNBR LCO at a 95/95 probability/ confidence level. The results of the analyses performed for SONGS Unit 2 cycle 2 are presented in this section.

3.1 LHR LCO

Following the analysis techniques described in Section 2.4.1, the COLSS synthesized Fq modeling errors are tabulated in Table 3-1 for three times in core life (BOC, MOC, EOC). All time-in-life dependent Fq modeling uncertainties were considered in evaluating the overall Fq penalty. However, the time-in-life that led to the most non-conservative modeling uncertainty was used to determine the overall Fq uncertainty factor. The individual uncertainty components of the Fq overall uncertainty factor are listed in Table 3-2. Combining the uncertainties associated with the LHR LCO results in an aggregate uncertainty of [ ] at a 95/95 probability/ confidence level. This uncertainty factor of [ ] when applied to the COLSS synthesized Fq, will assure that the COLSS Fq will be larger than the actual Fq at a 95/95 probability/confidence level at all times during the fuel cycle.

3.2 DNBR LCO

Following the analysis techniques presented in Section 2.4.2, the COLSS synthesized DNB-OPM modeling errors were calculated and are summarized in Table 3-3. The modeling error was analyzed as a function of time-in-life, but only the time-in-life which led to the most non-conservative modeling uncertainty was considered in calculation of the DNB-OPM overall uncertainty. The individual contributing uncertainty factors to the DNB-OPM overall uncertainty factor are presented in Table 3-2. Combining the uncertainties associated with the DNB-OPM LCO gives an overall uncertainty factor of [ ] at a 95/95 probability/confidence level. This overall uncertainty factor, when applied to the COLSS synthesized DNB-OPM, will assure that the COLSS DNB-OPM will be smaller than the actual DNB-OPM at a 95/95 probability/ confidence level at all times during the fuel cycle.

TABLE 3-1

COLSS SYNTHESIZED Fq MODELING ERROR[1] ANALYSIS

TIME IN CORE LIFE	NUMBER OF DATA POINTS (N)	MEAN ERROR ($\overline{X}_{FM}$)	95/95 TOLERANCE[2],[3] LIMIT $(TL)_{FM}$
BOC	[		
MOC			
EOC			]

(1) ERROR = $\left(\frac{\text{"SYN" Fq}}{\text{"ACTUAL" Fq}} - 1\right)$

(2) See References 9 and 10. Most conservative of normal or non-parametric values presented.

(3) If the error distribution is determined to be non-parametric, the value for $(k\sigma)_{FM}$ is calculated as

$$(k\sigma)_{FM} = -(TL)_{FM} \mp X_{FM}$$

TABLE 3-2

CONTRIBUTION OF INDIVIDUAL UNCERTAINTIES TO LCO OVERALL UNCERTAINTY FACTORS

UNCERTAINTY		LHR LCO	DNBR LCO
Modeling Error	$(\bar{X})_{FM}$, $(\bar{X})_{DM}$		
	$(k\sigma)_{FM}$, $(k\sigma)_{DM}$		
CECOR Fxy	$(\bar{X})_{FC}$, $(\bar{X})_{DC}$		
	$(k\sigma)_{FC}$, $(k\sigma)_{DC}$		
Fuel Rod Bow	$(k\sigma)_{PF}$		
Poison Rod Bow	$(k\sigma)_{PP}$		
Computer Processing	$(k\sigma)_{CP}$		
Reactor Core Simulator Modeling	$(k\sigma)_{FR}$		
Axial Densification	PA		
Engineering Factor	PE		

(1) includes power distribution synthesis uncertainty, in-core signal noise and CEA position error.

(2) includes [ ] in addition to the errors of (1).

TABLE 3-3

COLSS SYNTHESIZED DNB-OPM MODELING ERROR[1] ANALYSIS

TIME IN CORE LIFE	NUMBER OF DATA POINTS (N)	MEAN ERROR ($\bar{X}_{DM}$)	95/95 TOLERANCE[2],[3] LIMIT $(TL)_{DM}$
BOC	[		
MOC			
EOC			]

(1) ERROR = $\left(\frac{\text{"SYN" DNB-OPM}}{\text{"ACTUAL" DNB-OPM}} - 1\right)$

(2) See References 9 and 10. Most conservative of the normal or non-parametric values presented.

(3) Same as LHR except $(k\sigma)_{DM} = (TL)_{DM} - \bar{X}_{DM}$

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APPENDIX A

STOCHASTIC SIMULATION OF UNCERTAINTIES

A.1 Detector Signal Measurement and CEA Bank Position Measurement Uncertainties

In the SCU program, error components of in-core detector signals are [ ]. This error component is then added to the in-core signal generated from the core simulator and is used as input to the COLSS power distribution algorithm(A-1).

The location of each CEA bank is measured using pulse counters. An error component of each CEA bank measurement is selected [ ]. The sampled error is then added to the respective CEA bank position for input to the COLSS power distribution algorithm.

A.2 State Parameter Measurement Uncertainties

The DNB algorithm used for COLSS requires primary system pressure, core inlet temperature, core power, primary coolant flow rate, and hot-pin power distribution as input. Since RCS pressure, RCS temperature, and RCS flow affect the calculation of DNB-OPM, errors associated with these state parameters must be accounted for in the COLSS DNB-OPM uncertainty analysis. [ ] This procedure allows for direct simulation of the effect of the COLSS on-line temperature, pressure, and flow measurements and their uncertainties on the resultant DNB-OPM uncertainty. Therefore, uncertainties with respect to temperature, pressure, and flow are implicitly accounted for in the DNB-OPM modeling uncertainty.

A.3 DNB-OPM Algorithm Uncertainties

In the DNB-OPM overall uncertainty calculation, two distinct thermal hydraulic algorithms are involved. The off-line design T-H algorithm (CETOP-D)[A-2] represents the base-line DNB-OPM calculation. CETOP-1[A-3] is a simplified version of CETOP-D and performs the thermal hydraulic calculations in the reactor core simulator and COLSS (See Appendix A.3 of Part II). [

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A.4 Reactor Core Simulator Modeling Error

The reactor core simulator uses the FLARE neutronic model to predict representative power distributions. The FLARE model is tuned to a more accurate and rigorous ROCS neutronic simulator code. The reactor core simulator modeling error accounts for the effect of the FLARE modeling uncertainty on the reference LHR and DNB-OPM calculations.

A.5 REFERENCES FOR APPENDIX A

A-1 Combustion Engineering, Inc., "COLSS, Assessment of the Accuracy of PWR Operating Limits as Determined by the Core Operating Limit Supervisory System", CENPD-169-P, July, 1975.

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APPENDIX B

AXIAL SHAPE INDEX UNCERTAINTY

The axial shape index (ASI) for the core average power distribution is computed from the power in the lower and upper halves of the core:

$$ASI = \frac{P_L - P_U}{P_L + P_U} \quad \text{(B-1)}$$

where

P_L and P_U are, respectively, power in the lower half and the upper half of the core.

The ASI error is defined by:

ASI Error = COLSS ASI - Reactor Core Simulator ASI (B-2)

The core average ASI uncertainty analysis is performed by comparing the COLSS calculated ASI and the reactor core simulator ASI. The resulting error distributions are analyzed to obtain the upper and lower 95/95 tolerance limits. The core average ASI uncertainties are presented in Table B-1.

TABLE B-1

CORE AVERAGE ASI ERROR* ANALYSIS

BURNUP	NUMBER OF DATA POINTS	MEAN ERROR	STANDARD DEVIATION	LOWER 95/95 LIMIT	UPPER 95/95 LIMIT
BOC					
MOC					
EOC					

* ASI ERROR = (COLSS ASI - SIMULATOR ASI)

COMBUSTION ENGINEERING, INC.