COMBUSTION ENGINEERING, INC.

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STATISTICAL COMBINATION OF UNCERTAINTIES

PART III

Uncertainty Analysis of Limiting Conditions for Operation
C-E System 80 Nuclear Steam Supply Systems

REACTOR DESIGN

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Combustion Engineering, Inc.
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ABSTRACT

Part III of the Statistical Combination of Uncertainties (SCU) reports 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 the Combustion Engineering (C-E) Nuclear Steam Supply Systems (NSSS). 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 reports describe 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.

* Submitted as Enclosure 1-P to letter LD-82-054 , A. E. Scherer to D. G. Eisenhut, dated May 14, 1982.

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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-OPM Algorithm for Safety Analysis
CETOP-1	On-Line DNB-OPM Algorithm Used in COLSS and Core Simulator
CETOP-2	On-Line DNB-OPM 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	Emergency 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
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 in-core detector signal measurement
2. Uncertainty in Control Element Assembly (CEA) position measurement
3. Uncertainties in temperature, pressure, and flow measurements
4. Uncertainty in measurement of planar radial peaking factors (Fxy) using CECOR[2]
5. Uncertainty in Core Operation Limit Supervisory System (COLSS) LHR calculation due to the COLSS power distribution synthesis for COLSS LHR algorithm.
6. Uncertainty in COLSS DNB-OPM calculation due to the COLSS power distribution synthesis for COLSS DNB-OPM algorithm
7. Uncertainty in COLSS DNB-OPM algorithm with respect to safety analysis DNB-OPM algorithm
8. Computer processing uncertainty
9. Fuel and poison rod bow uncertainties
10. Global 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, and 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 assists in assuring that no anticipated operational occurrence will result in exceeding the Specified

Acceptable Fuel Design Limits (SAFDL) on DNB 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 DNB and LHR operating limits and monitored NSSS variables is given in Table 1-1.

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

The Statistical Combination of Uncertainties (SCU) 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 conditons.

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 CE System 80.

1.4 SUMMARY OF RESULTS

The analysis techniques described in Section 2.0 were applied to C-E System 80. 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
Radial Peaking Factor	CEA Positions
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 analyses performed to determine overall uncertainty factors which are applied to the COLSS calculations of the LHR and DNB-OPM to ensure 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 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 were performed by comparing the three-dimensional power peaking factor (Fq) and DNB-OPM obtained from the reactor core simulator[1] to those calculated by COLSS as shown in Figures 2-1 and 2-2. The reactor core simulator generates the three-dimensional core power distributions which reflect changes in typical operating conditions. F_q and DNB-OPM modeling uncertainties are statistically combined with other uncertainties in calculating COLSS overall uncertainty factors for the COLSS LHR and DNB-OPM calculations. The uncertainty analysis performed in this report also involves the stochastic simulation of the state parameter measurement uncertainties for the LHR and DNB-OPM calculations[5]. 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) were used in the determination of the overall uncertainty factors for the LHR and DNB-OPM calculations. The cases (total of 3600) considered herein were chosen to encompass steady state and quasi-steady state plant operating conditions throughout the cycle lifetime. Power distributions were 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 concentration (equilibrium, load maneuver, oscillation).

2.3.2 LHR LCO STATISTICAL METHODS

The reactor core simulator was used to generate the hot pin power distribution which served 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 Fq. 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 errors are analyzed for each case of each time-in-life. Approximately 3600 cases are analyzed at BOC, MOC, and EOC conditions. Each error distribution is evaluated to obtain the mean Fq error ($\overline{X_F}$) and the standard deviation (σ_F).

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

$$\overline{X}_F = \frac{\sum_{i=1}^{N} X_F^i}{N} \qquad (2\text{-}2)$$

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

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,one-sided tolerance limit factor, K, is a number which accounts for the sampling variations in the sample mean ($\overline{X_F}$) and the standard deviation (σ_F). A normality test of the error distribution is performed by using the D-prime statistic value(6-7) 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(7-8) (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-parameteric 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, faster running DNB-OPM algorithm CETOP-1.(10). [

]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 state 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 reacor core simulator DNB-OPM for the i-th case. The DNB-OPM errors are analyzed separately for each time-in-life for conservatism. Each error distribution is analyzed for normal or non-parametric behavior to calculate the mean DNB-OPM error ($\overline{X_D}$), standard deviation (σ_D), and one-sided 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 measurement (pulse counter position) 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 simple five element Fourier fitting technique is employed in COLSS to get 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-cycle. The mean Fq error ($\overline{X_F}$), 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, and the CEA position measurement.

2.4.1.2 CECOR FXY UNCERTAINTY

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

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[13] considers the global effect of the shrinkage of the fuel pellet stack, due to in-pile sintering, on the COLSS Fq calculations. [ ]

FUEL AND POISON ROD BOW UNCERTAINTIES

The fuel and poison rod bow uncertainties(14) consider the effect of "bowing" of the fuel and poison rods, due to heating and irradation, on the COLSS Fq calculations. The factors will be used as 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 7600 computer and the on-site computer on the COLSS Fq calculations. The computer processing uncertainty will be used as part of the composite Fq modeling uncertainty.

ENGINEERING FACTOR UNCERTAINTY

The engineering factor considers the effect on the COLSS Fq calculation due to fuel manufacturing tolerance(13). This factor 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 error components. This overall uncertainty factor is made up of a composite Fq modeling uncertainty and axial fuel densification 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 CPC inferred value of Fq for the i-th case, respectively. A composite error ($X_{FT}{}^i$) of the Fq modeling uncertainty and the CECOR Fxy uncertainty can be deterministically calculated as follows:

$$X_{FT}^{i} = \left(\frac{C_i}{F_i}\right)\left(\frac{G_i}{P_i}\right) - 1 \tag{2-7}$$

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

$$X_{FT}{}^{i} = X_{FM}{}^{i} + X_{FC}{}^{i} + (X_{FM}{}^{i} * X_{FC}{}^{i}) \tag{2-8}$$

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

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

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

[ ] (2-10)

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

$$PM_F = \frac{1}{1 + TL_F} \tag{2-11}$$

where

$$TL_F = \overline{X}_{FT} - (K\sigma)_{FT} \tag{2-12}$$

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

The last step to determine 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,

* See Appendix A4.

[ ] (2-13)

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

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

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 DNB-OPM modeling uncertainty, a [stochastic simulation] program was employed. The SCU program [stochastically simulates] the measurement uncertainties and operating ranges associated with RCS state parameters along with the on-line to off-line DNB-OPM 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 $(K\sigma)_{DT}$ and is part of the DNB-OPM composite modeling uncertainty. This computer processing uncertainty ($K\sigma_{CP}$) is calculated using the following equation:

[ ] (2-16)

[ ]

[ ] (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 DNB correlation[11]. The MDNBR for LCO includes the uncertainties associated with system parameters which describe the physical system. These system parameters are composed of core geometry, pin-by-pin radial power distributions, inlet and exit flow boundary conditions, etc. In the statistical combination of system parameter uncertainties[15], 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. CHF 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, 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. Figure 2-3 shows the calculational sequence to determine the overall DNB-OPM uncertainty factor.

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

[ ] (2-18a)

and the CECOR F_{xy} " $K\sigma$ " 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 CECOR Fxy ($K\sigma_{DC}$), DNB-OPM algorithm ($K\sigma_{DM}$), rod bow penalties ($K\sigma_{PF}$, $K\sigma_{PP}$), DNBR computer processing ($K\sigma_{CP}$), and FLARE/ROCS modeling error ($K\sigma_{FR}$). Using the root-sum-square technique, this composite $(K\sigma)_{DT}$ is calculated by:

[ ] (2-20)

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

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

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:

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 STATE PARAMETERS

PARAMETERS	UNIT	RANGES	MEASUREMENT UNCERTAINTY
Core Inlet Colant Temperature	(°F)		
Primary Coolant Pressure	(psia)		
Primary Coolant Mass Flow	(GPM)		

FIGURE 2-1

COLSS SIMULATION FOR F_q

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 C-E System 80 are presented in this section.

3.1 LHR LCO

Following the analysis techniques described in Section 2.4.1, COLSS synthesized Fq modeling errors are tabulated in Table 3-1 for the 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 worst 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. A stochastic simulation of uncertainties associated with the LHR LCO results in an aggregate uncertainty of [ ] at a 95/95 probability/confidence limit. 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 mean values, standard deviations, and lower tolerance limit of the COLSS synthesized DNB-OPM modeling errors were obtained and are summarized in Table 3-3. The modeling error was analyzed as a function of the core life, but only the burnup which led to the most 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 of the uncertainties associated with the DNB-OPM LCO gives an overall uncertainty factor of [ ] at a 95/96 probability/confidence limit. 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 ($\bar{X}_F$), %	STANDARD[3] DEVIATION (σ), %	95/95 TOLERANCE[2],[3] LIMIT $(TL)_F$
BOC	[			
MOC				
EOC				]

(1) ERROR $= \left(\frac{\text{"SYN" Fq}}{\text{"ACTUAL" Fq}} - 1 \right) * 100$

(2) See References 8 and 9. Normal or non-parametric values presented.

(3) If error distribution is determined to be non-parametric, the value for $(K\sigma)_F$ is calculated as

$$(K\sigma)_F = -(TL)_F + \bar{X}_F$$

TABLE 3-2

CONTRIBUTION OF INDIVIDUAL UNCERTAINTY TO LCO OVERALL UNCERTAINTY FACTORS

UNCERTAINTY		LHR LCO	DNBR LCO
3-D Peak Modeling(*)	$\bar{X}$		
	$K\sigma$		
CECOR Fxy	$\bar{X}$		
	$K\sigma$		
Engineering Factor			
Fuel Rod Bow			
Poison Rod Bow			
Axial Densification			
Computer Processing			
DNB-OPM Modeling with SCU(**)	$\bar{X}$		
	$K\sigma$		
FLARE/ROCS Modeling			

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

(**) includes [ ] in addition to errors of (*).

TABLE 3-3

COLSS SYNTHESIZED DNB-OPM MODELING ERROR[1] ANALYSIS

TIME IN CORE LIFE	NUMBER OF DATA POINTS (N)	MEAN ERROR (X_D), %	STANDARD[3] DEVIATION (σ), %	95/95 TOLERANCE[2],[3] LIMIT $(TL)_D$
BOC				
MOC				
EOC				

(1) $\text{ERROR} = \left(\frac{\text{"SYN" DNB-OPM}}{\text{"ACTUAL" DNB-OPM}} - 1 \right) * 100$

(2) See References 8 and 9. . . Normal and non-parametric values presented.

(3) Same as LHR except $(K\sigma)_D = (TL)_D - \overline{X}_D$

REFERENCES

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APPENDIX A

STOCHASTIC SIMULATION OF UNCERTAINTIES

A1. 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.

The location of each CEA bank is measured using the pulse counter position. 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.

A2. State Parameter Measurement Uncertainties

The DNB-OPM algorithm(A-1) 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, DNB-OPM uncertainties with respect to temperature, pressure, and flow are implicitly accounted for in the DNB-OPM modeling uncertainty.

A3. DNB-OPM Algorithm Uncertainties

In the DNB-OPM overall uncertainty calculation, two distinct thermal hydraulic algorithms are involved. The off-line safety-analysis 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. [

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A4. FLARE/ROCS 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 code. The FLARE/ROCS modeling error takes account for the effect of the FLARE modeling uncertainty on the reference LHR and DNB-OPM calculations.

A5. 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:

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

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 analyses are 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 for C-E System 80 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)