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<Technical Note>

eXtended Statistical Combination of Uncertainties (XSCU) Method for Digital Nuclear Power Plants

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Abstract

A technically more direct Statistical Combination of Uncertainties (SCU) method, eXtended SCU (XSCU), was developed to statistically combine the uncertainties associated with the DNBR alarm setpoint and the DNBR trip setpoint of digital nuclear power plants. The Modified SCU (MSCU) method is currently used as the USNRC approved design method to perform the same function. In this study, the MSCU and XSCU methods were compared in terms of the total uncertainties, and the thermal margins to the DNBR alarm and trip setpoints. The MSCU method resulted in small total uncertainties due to large negative biases which are unphysical. The XSCU method gives virtually unbiased total uncertainties which are physically meaningful in order to represent the actual magnitude of the total uncertainties associated with the DNBR alarm and trip setpoints. But the thermal margins to the DNBR alarm and trip setpoints by the MSCU method agree with those by the XSCU method within allowable statistical variations.

1. Introduction

COLSS[1] stands for Core Operating Limit Supervisory System which is designed to assist the plant operator in monitoring the Limiting Conditions for Operation (LCOs). One of the COLSS functions is to compute the DNBR power operating limit from process variable measurements and the margin to the DNBR power operating limit on the plant computer.

COLSS initiates appropriate alarm and informative messages when the monitored margin decreases below its alarm setpoint.

CPCS stands for Core Protection Calculator System which is a part of Reactor Protection System (RPS). CPCS consists of four Core Protection Calculators (CPCs) and two Control Element Assembly Calculators(CEACs). CPC[2] computes the DNBR from the process variable measurements and compares it with the DNBR trip setpoint. CPC initiates a reactor trip when the DNBR trip setpoint is exceeded. CEAC[3] transmits the information associated with Control Element Assembly (CEA) position to CPC.

The MSCU (Modified Statistical Combination of Uncertainties) method was designed to improve plant operating performance and flexibility, and to reduce the incidence of unnecessary reactor trip by reducing excessive conservatism in the DNBR overall uncertainty factors for COLSS and CPCS. The reductions in overall uncertainty factors result primarily from statistical combination of system parameter uncertainty components which were applied semi-deterministically in the standard SCU (Statistical Combination of Uncertainties) method. The major change in the MSCU method was to statistically include the system parameter uncertainty DNBR probability density function (pdf) in the COLSS and CPC DNBR overall uncertainty factor calculations via stochastic simulation. The other changes are described in detail in Reference 4.

It was decided for the MSCU to maintain the standard SCU DNBR limit (typically 1.2-1.3), i.e., 95/95 upper tolerance limit of DNBR pdf, for COLSS/CPCS setpoints and to effectively credit the over-conservation of this high DNBR limit in the overall uncertainty calculations. A technically more direct way called XSCU (eXtended Statistical Combination of Uncertainties), which is developed here, is to use the mean value of the system parameter uncertainty DNBR pdf as the COLSS/CPCS DNBR setpoints to include the uncertainties in the COLSS and CPC overall uncertainty analysis.

Overviews of the above three SCU methods used for COLSS and CPCS overall uncertainty calculations are described in Section 2. Section 3 describes detailed procedures for the applications of the MSCU and XSCU methods. Section 4 documents the results of thermal margins to DNBR alarm and trip setpoints for both MSCU and XSCU. The calculations were based on the YGN 3&4 Cycle 1 final design data. Section 5 describes the conclusions.

2. Statistical Combination of Uncertainties

2.1. Standard SCU

The uncertainties involved in the SCU methods are divided into two categories. The first category, referred to as "system parameter" uncertainties[5], includes engineering factors, CHF correlation uncertainties and thermal-hydraulic code modeling uncertainties. The uncertainties in this group are statistically combined to generate a DNBR probability density function (pdf). The 95/95 probability/confidence limit of this DNBR pdf is deterministically combined with the fuel rod bow and the HID-1 grid penalties to determine the minimum DNBR limit to be applied in COLSS and CPC.

The second category, referred to as "state parameter" uncertainties[6,7], includes measured state parameters, radial peaking factor measurement, simulator model, computer processing and startup measurement uncertainties. The state parameters, algorithm and startup measurement uncertainties are stochastically simulated to generate a state parameter pdf. The

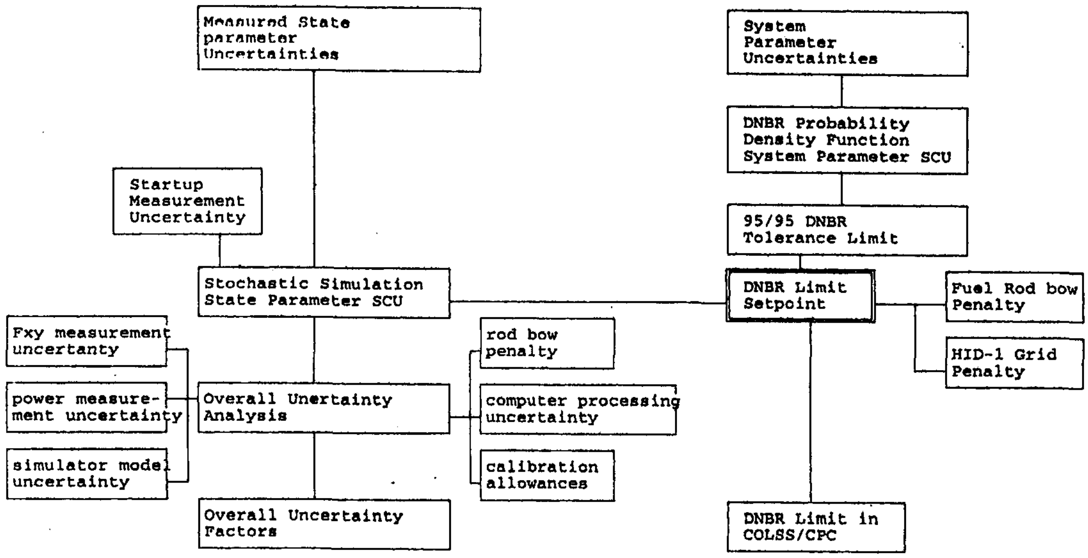

Fig. 1. Standard SCU Method Schematic

95/95 probability/confidence level of this function is then root-sum-squared with the other uncertainties to determine the CPC and COLSS overall uncertainty factors.

Even though uncertainties within each group are statistically combined and a 95/95 probability/confidence level is generated for each group, the resultant uncertainties of the two groups are effectively combined in a deterministic manner due to separate statistical applications in the DNBR limit and the overall uncertainty factors.

In the standard SCU method, power measurement uncertainties are applied separately from the system and state parameter uncertainty factors. COLSS normally uses secondary calorimetric power as the standard and therefore the power measurement uncertainty for COLSS consists of the secondary calorimetric uncertainty. The CPC neutron flux power measurement uncertainty factor is calculated by a deterministic combination of the secondary calorimetric uncertainty, a calibration allowance, and the neutron flux power synthesis uncertainty. Figure 1 is the schematic of the standard SCU method.

2.2. Modified SCU

The MSCU method was designed to improve plant operating performance and flexibility, and reduce the incidence of unnecessary reactor trip by reducing excessive conservatism in the DNBR overall uncertainty factors for COLSS and CPC. The reductions in overall uncertainty factors result primarily from statistical combination of several uncertainty components previously applied deterministically. The changes made to the standard SCU method are the following :

1) Include the system parameter uncertainty DNBR pdf in the COLSS and CPC DNBR overall uncertainty factor calculations via stochastic simulation.
2) Include the secondary calorimetric power measurement uncertainty in the state parameter stochastic simulation for COLSS and CPC DNBR overall uncertainty factors.
3) Include the neutron flux power synthesis

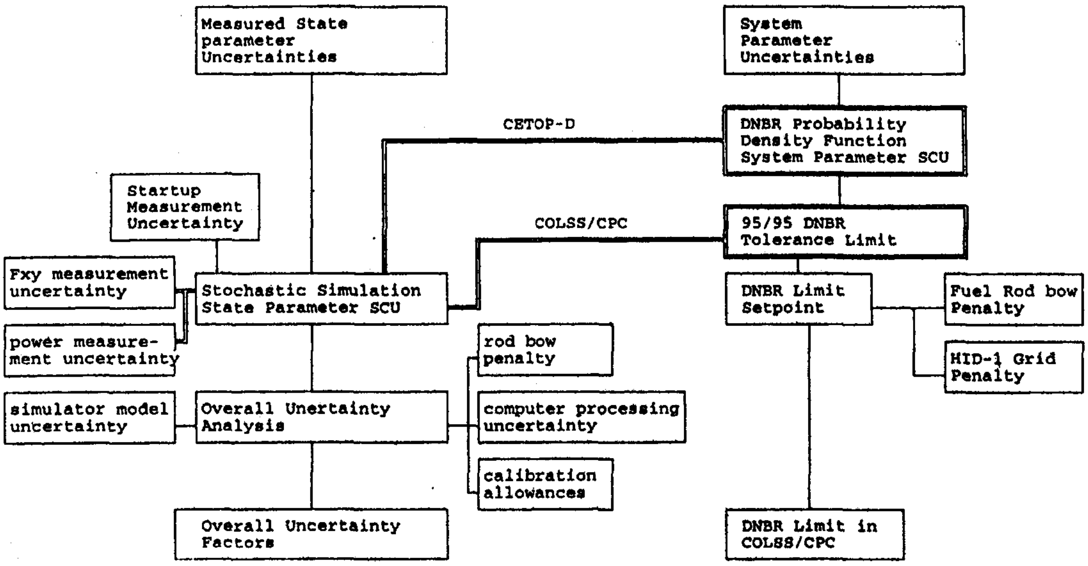

Fig. 2. Modified SCU Method Schematic

uncertainty in the state parameter stochastic simulation for the CPC DNBR overall uncertainty factors.

4) Include the radial peaking factor uncertainty pdf in the state parameter stochastic simulation for COLSS and CPC.

Since item 1) is the major change from the standard SCU, and the only difference between the Modified and eXtended SCU methods, it is described in detail in this paper. In the MSCU method, the system parameter uncertainties are combined in the same way with standard SCU method to determine the DNBR pdf[5]. However, instead of using the 95/95 probability/confidence tolerance limit of the DNBR pdf, DNBR limits are sampled from the DNBR pdf itself in the state parameter stochastic simulations. Thus, both the system and state parameter uncertainties are combined statistically in the COLSS and CPC overall uncertainty factors.

Figure 2 provides the schematic of the Modified SCU method. As shown in Figure 2, the DNBR limits sampled from the DNBR pdf are used in the DNB-OPM* calculations by the best estimate design code, CETOP-D[8]. However, the 95/95 tolerance limit of the DNBR pdf is used in the DNB-OPM calculations of the COLSS/CPC simulators in order to maintain the standard SCU DNBR limit which is installed in the on-line COLSS and CPC.

The use of 95/95 DNBR tolerance limit (typically 1.2-1.3) in COLSS/CPC will result in significantly lower COLSS/CPC DNB-OPM than the CETOP-D DNB-OPM. This is because the DNBR limit for the CETOP-D calculations would be approximately mean value of the DNBR pdf

* OverPower Margin to a condition that the calculated minimum DNBR reaches the DNBR limit.

** There is a fuel design criterion that there be at least a 95% probability at a 95% confidence level that the hot fuel rod in the core does not experience a DNB during normal operation or anticipated operational occurrence. The criterion is fulfilled by taking 95%/95% probability/confidence lower tolerance limit of the probability density function of E i.

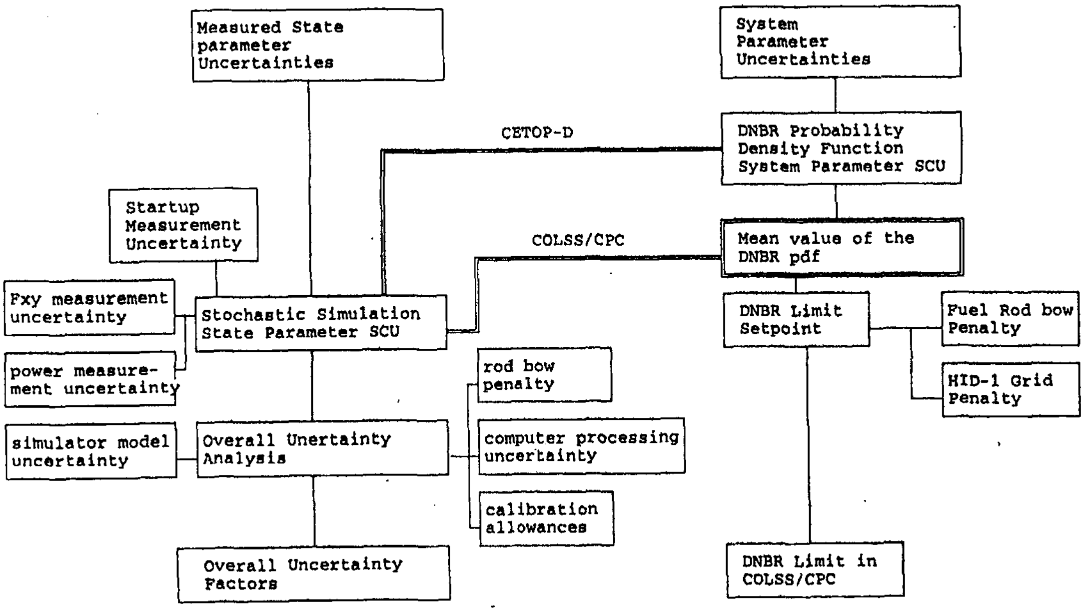

Fig. 3. eXtended SCU Method Schematic

(near 1.0) since the DNBR limits are statistically sampled from the DNBR pdf. Hence, the resultant DNB-OPM error, which is defined below, distributions will be significantly biased to the negative direction thereby giving smaller overall uncertainty factors.

$$E_i^{**} = \frac{\text{DNB-OPM}_{\text{COLSS/CPC}} - \text{DNB-OPM}_{\text{CETOP D}}}{\text{DNB-OPM CETOP-D}} \qquad (1)$$

where i - Case number

$\text{DNB-OPM}_{\text{COLSS/CPC}}$ - DNB-OPM calculated by either COLSS or CPC

$\text{DNB-OPM}_{\text{CETOP-D}}$ -DNB-OPM calculated by CETOP-D

However, the base COLSS/CPC DNB-OPMs without the uncertainty factors would be also small because the 95/95 tolerance limit of the DNBR pdf should be installed as the DNBR limit in on-line COLSS and CPC.

2.3. eXtended SCU

A technically more direct way, called XSCU (eXtended Statistical Combination of Uncertainties), is to use the mean value of the system parameter uncertainty DNBR pdf as the COLSS/CPCS DNBR setpoints to include the uncertainties in the COLSS and CPC overall uncertainty analysis. This approach will result in a DNBR limit close to 1.0 which can appear to allow the COLSS/CPS setpoints significantly closer to DNB condition. This approach is shown in Figure 3 to compare with the Modified SCU method. Figure 3 shows the use of the mean value of the DNBR pdf both in the overall uncertainty analysis and in the on-line COLSS/CPC. This is a direct approach to statistically combine the uncertainties in the system parameters and the uncertainties in the state parameters. Unlikely for the MSCU method, the application of XSCU method will not bias the

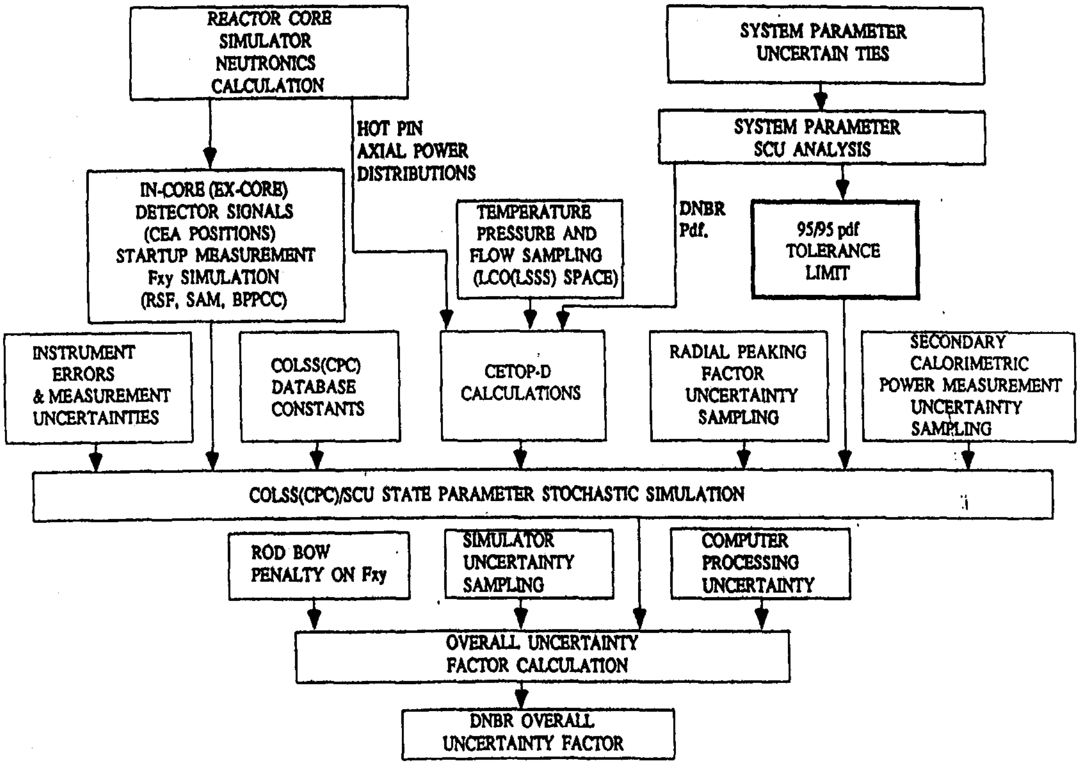

Fig. 4. COLSS/CPC Overall Uncertainty Analysis with MSCU

resultant DNB-OPM error distributions. This elimination of the artificial biases will result in bigger DNB-OPM overall uncertainty factors but physically more meaningful uncertainties. However the reduced DNBR limit in on-line COLSS and CPC will increase the base margins to the DNBR alarm and trip setpoints. The YGN 3&4 Cycle 1 final design data were used to evaluate the overall uncertainty factors and thermal margins to the DNBR alarm and trip setpoints by both MSCU and XSCU methods. The MSCU results were then compared with the XSCU results in Section 4.

3. Overall Uncertainty Analysis and DNB Thermal Margin Evaluation

3.1. Overall Uncertainty Analysis

The system parameter SCU method5) is used to determine the DNBR pdf. The uncertainty components combined to drive this pdf are listed in Table 1. The resultant pdf for YGN 3&4 Cycle 1 is a normal distribution with mean of 1.038 and standard deviation of 0.1379. However, subsequent penalties imposed by USNRC should be included on these values. The DNBR limit for the on-line COLSS and CPC is defined as :

$$\text{DNBR Limit} = TL \times P_{BOW} + P_{HID} \qquad (2)$$

where TL = 95/95 probability/confidence tolerance limit of DNBR pdf

P_{BOW} = Rod bow penalty (1.75%)

Table 1. Components Combined in the DNBR pdf

Core inlet flow distribution
Engineering factor on enthalpy rise
Systematic fuel rod pitch
Systematic fuel clad O.D.
Engineering factor on heat flux
CE-1 CHF correlation
Thermal-Hydraulic computer code uncertainty

P_{HID} = HID-1 grid penalty (0.01)

The DNBR pdf and its tolerance limit are used in the COLSS and CPC DNBR overall uncertainty analysis while the DNBR limit generated by Eq. (2) is used in the on-line COLSS and CPC for both standard SCU and MSCU.

The COLSS and CPC DNBR overall uncertainty analysis process using Modified SCU is illustrated in Figure 4. The COLSS/SCU simulator (COLSIM) for the COLSS OUA (Overall Uncertainty Analysis) and the CPC/SCU simulator (CPCSIM) for the CPC OUA stochastically simulates the measurement uncertainties and operating ranges associated with the RCS pressure, inlet temperature, flow, CEA position, in-core (or ex-core) detectors, Fxy measurement and secondary calorimetric power measurement uncertainties, and samples from DNBR pdf for system parameters. Table 2 lists the state parameter measurement uncertainty components simulated in COLSS/SCU and CPC/SCU simulators. The simulation is performed for approximately 1200 cases at each of four times in life (BOC, IOC, MOC, and EOC).

As described in Section 2, the stochastic simulation of the system parameter uncertainties in MSCU is performed by applying the DNBR pdf in the best estimate (CETOP-D) DNB-OPM calculation and using the 95/95 tolerance limit in the COLSS and CPC DNB-OPM calculations. The DNB-OPM error defined as in Eq. (1) is calculated for approximately 1200 cases and the resultant error distribution is evaluated. The tolerance limit of the DNB-OPM error distribution is determined based on distribution type which is determined by the normality test[9]. The tolerance limit is then statistically combined with the simulator model and computer processing uncertainties and the fuel rod bow penalty to determine the DNBR overall uncertainty factors, EPOL2 for COLSS and BERR1 for CPC, which are respectively installed in COLSS and CPC. Use of the overall uncertainty factor (EPOL2) for the COLSS assures, at least a 95% probability and 95% confidence level, that the "ACTUAL" DNB-OPM will be larger than the COLSS DNB-OPM. Use of the overall uncertainty factor (BERR1) for the CPC assures, at least a 95% probability and at 95% confidence level, that the "ACTUAL" DNB-OPM will be larger than the CPC DNB-OPM. The COLSS and CPC DNBR overall uncertainty analysis process using the XSCU is illustrated in Figure 5. It is noted that the only difference from the MSCU process is in the stochastic simulation of the system parameter uncertainties. Unlikely

Table 2. COLSS/CPC State Parameter Measurement Uncertainty Components

Core inlet coolant temperature
Primary coolant pressure
Primary coolant flow
In-core detector signal (COLSS)
Ex-core detector signal (CPC)
CEA position
Startup measurements (CPC)
- Rod Shadowing Factor
- Shape Annealing Matrix
- Boundary Point Power Correlation Coefficients

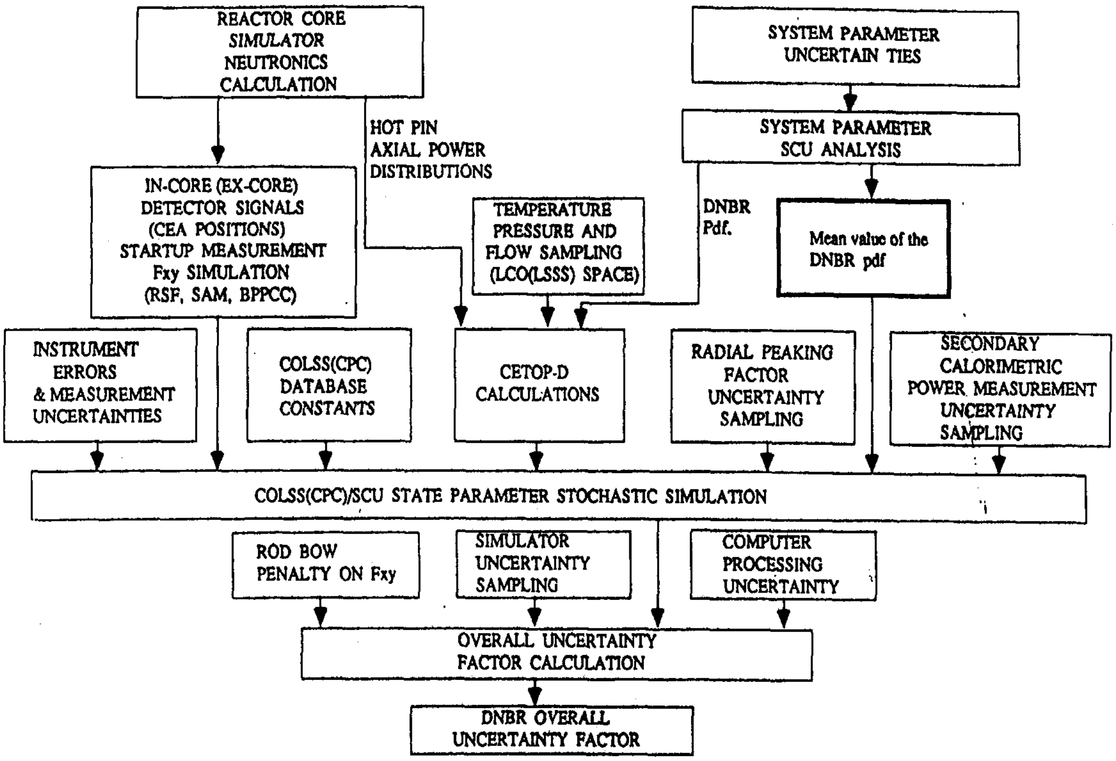

Fig. 5. COLSS/CPC Overall Uncertainty Analysis with XSCU

for the MSCU process, the stochastic simulation in XSCU is performed by using the mean of the DNBR pdf in the COLSS and CPC DNB-OPM calculations.

The COLSS/CPC overall uncertainty analyses were performed using the YGN 3&4 Cycle 1 final design data. Table 3 lists the DNBR pdf data and the DNBR limits for MSCU and XSCU. It should be noted that the mean (μ) of DNBR pdf is obtained by adding a convergence tolerance of 0.005 to the raw mean (1.038) for the DNB-OPM calculation. The DNB-OPM is calculated by power iteration in COLSS/SCU and CPC/SCU simulators. It is also noted that the DNBR limit used in overall uncertainty analysis does not include the rod bow penalty and the HID-1 grid penalty but the DNBR limit installed in the on-line COLSS and CPC does because they are additionally required by the USNRC separately

Table 3. YGN 3&4 Cycle 1 DNBR pdf and DNBR Limits

	MSCU	XSCU
DNBR pdf		
Type	Normal	Normal
μ	1.043	1.043
σ	0.1397	0.1397
DNBR Limit in COLSS/CPC Overall Uncertainly Analysis	1.273	1.043
DNBR Limit in the On--line COLSS/CPC	1.305	1.071

Table 4. Results of COLSS Overall Uncertainty Analyses and Thermal Margin Calculations

	BOC		IOC		MOC		EOC	
	MSCU	XSCU	MSCU	XSCU	MSCU	XSCU	MSCU	XSCU
Overall Uncertainty Analysis								
- mean(μ)	−0.06101	0.01149	−0.07540	−0.00207	−0.07236	−0.00488	−0.07798	−0.01222
-standard deviation(σ)	0.05484	0.05895	0.05605	0.05899	0.05446	0.05663	0.05177	0.05581
-1+EPOL2	1.03942	1.13213	1.03198	1.10513	1.02883	1.10182	1.02172	1.09161
-difference * (%)	-	8.9	-	7.1	-	7.1	-	6.8
Base DNB-OPM	141.5	152.2	139.7	151.0	132.9	143.8	135.8	145.7
DNB Thermal Margin	115.8	114.4	115.2	116.2	110.0	111.1	113.1	113.6

$* \left(\dfrac{1+\mathrm{EPOL2}_{\mathrm{XSCU}}}{1+\mathrm{EPOL2}_{\mathrm{MSCU}}}-1\right)\times 100$

from the SCU procedures.

3.2. DNB Thermal Margin Evaluation

The base DNB margin is defined as the margin to DNBR alarm setpoint (COLSS DNB-OPM) or to DNBR trip setpoint (CPC DNB-OPM) at nominal plant operating conditions, hot full power, all rods-out, equilibrium xenon, without uncertainties associated with the COLSS/CPC DNB-OPM calculations. The DNBR limit in the on-line COLSS and CPC is used to calculate the base COLSS DNB-OPM and CPC DNB-OPM, respectively. The DNB thermal margin of Reference 10 is defined as the DNB margin with appropriate uncertainties. These uncertainties include Required Overpower Margin (ROPM)*** from transients analysis for COLSS, overall uncertainty factors (EPOL2 and BERR1), azimuthal tilt allowance. The COLSS and CPC DNB thermal margins are calculated from the base DNB-OPMs by applying the above uncertainties following the standard procedures of Reference 10.

4. Results and Discussion

The COLSS and CPC overall uncertainty analyses were performed with both MSCU and XSCU at each of four times in life (BOC, IOC, MOC, EOC). Table 4 lists the results of COLSS OUA, i.e., the COLSS DNBR overall uncertainty factor (EPOL2), with additional statistic information. Table 4 also lists the base DNB-OPM and the DNB thermal margin which were calculated as described in Section 3. Similar data for CPC are listed in Table 5. BERR1 in Table 5 is the CPC DNBR overall uncertainty factor.

As shown in Table 4 and Table 5, the COLSS/CPC overall uncertainty factors (EPOL2, BERR1) by the MSCU are smaller than those by the XSCU, which is expected due to the negative bias of the mean (μ) of the resultant error distributions, which, in turn, result from the use of high DNBR limit in the MSCU. However, the use of high DNBR limit in the MSCU resulted in low base DNB-OPM. It is therefore necessary to compare the two SCU methods in terms of DNB thermal margin which combines the base DNB-OPM and the overall uncertainty factors. As

***The margin set aside to accommodate the thermal margin degradation during limiting Anticipated Operational Occurrence or limiting Accident.

Table 5. Results of CPC Overall Uncertainty Analyses and Thermal Margin Calculations

	BOC(0 GWD/T)		IOC(3 GWD/T)		MOC(8 GWD/T)		EOC(13.65GWD/T)	
	MSCU	XSCU	MSCU	XSCU	MSCU	XSCU	MSCU	XSCU
Overall Uncertainty Analysis								
- mean(μ)	−0.0540	0.0244	−0.0617	0.0159	−0.0665	0.0101	−0.0779	−0.0051
-standard deviation(σ)	0.0641	0.0684	0.0653	0.0696	0.0695	0.0748	0.0720	0.0767
-BERR1	1.0615	1.1569	1.0664	1.1496	1.0579	1.1488	1.0522	1.1330
-difference * (%)	-	9.0	-	7.8	-	8.6	-	7.7
Base DNB-OPM	137.6	148.2	136.6	147.3	125.9	136.9	127.9	138.7
DNB Thermal Margin	127.0	126.5	126.5	126.5	117.8	118.0	120.3	121.1

* $\left(\frac{BERR1_{XSCU}}{BERR1_{MSCU}} - 1\right) \times 100$

described in Section 3, the DNB thermal margin is calculated by dividing the base DNB-OPM by the associated uncertainties including the overall uncertainty factors.

The calculated DNB thermal margin values are listed in Table 4 for COLSS and Table 5 for CPC. The COLSS DNB thermal margin by the XSCU is a little smaller than that by the MSCU at BOC but is slightly larger at other times in life. The smaller COLSS DNB thermal margin by the XSCU at BOC is due to the DNB-OPM error distribution type. The BOC error distribution by the XSCU is non-Normal distribution but the error distribution by the MSCU is close to Normal distribution. However, the error distributions at other times in life are close to Normal distribution irrespective of the SCU methods. In general, the 95/95 tolerance limit of non-Normal distribution is bigger than that of Normal distribution since the non-Normal distribution uses bigger upper/lower tolerance limits. Hence, the COLSS BOC overall uncertainty factor by the XSCU is bigger than that of Normal DNB-OPM error distribution, rendering smaller thermal margin value. The differences of the COLSS DNB thermal margins at other than BOC are less than 1% and they were resulted from the slight differences in the resultant error distributions themselves. These differences could be reduced if the number of sampled cases sufficiently increases. For CPC, the XSCU results show good agreement with the MSCU results except at BOC. As was for COLSS, the BOC error distribution by MSCU is close to Normal distribution but the XSCU error distribution is non-Normal distribution. Hence, the CPC BOC DNB thermal margin by the MSCU is slightly bigger than that by the XSCU. It is therefore concluded that the XSCU results agree with the MSCU results within statistical variations.

5. Conclusions

The technically more direct SCU method, XSCU, was applied to perform the COLSS/CPC overall uncertainty analyses and thermal margin calculations. The thermal margin results were then compared with those by the MSCU which is currently used in the COLSS/CPC analyses. The MSCU thermal margin results agree with the XSCU results within statistical variations. It was therefore confirmed that both MSCU and XSCU methods effectively combine the uncertainties of the system parameters in statistical manner as they are designed. However, the MSCU method resulted in biased total penalties which misleadingly represents the physical uncertainties in the DNBR calculations to alarm and trip setpoints. In contrast, the XSCU method combines the system parameter uncertainties by direct statistical treatment so that the XSCU results represent physically meaningful uncertainties. Therefore, it can be concluded that the use of XSCU method is preferable even if this method gives an appearance of operating nuclear power plants near DNB condition since the COLSS/CPC DNBR setpoint is close to 1.0.

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