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Development of Uncertainty Analysis Method for SMART Digital Core Protection and Monitoring System

Bon-Seung Koo, Wang-Kee In and Dae-Hyun Hwang
Korea Atomic Energy Research Institute, 1045, Daedeokdaero, Yuseong-gu, Daejon, 305-353, Korea
bskoo@kaeri.re.kr

1. Introduction

The Korea Atomic Energy Research Institute has developed a system-integrated modular advanced reactor (SMART) for a seawater desalination and electricity generation. Online digital core protection and monitoring systems, called SCOPS and SCOMS respectively were developed[1]. SCOPS calculates minimum DNBR and maximum LPD based on the several online measured system parameters. SCOMS calculates the variables of limiting conditions for operation.

KAERI developed overall uncertainty analysis methodology which is used statistically combining uncertainty components of SMART core protection and monitoring system[2,3]. By applying overall uncertainty factors in on-line SCOPS/SCOMS calculation, calculated LPD and DNBR are conservative with a 95/95 probability/confidence level. In this paper, uncertainty analysis method is described for SMART core protection and monitoring system.

2. Analysis Techniques

2.1 General Strategy

MASTER code used as a reactor core simulator generates typical 3-dimensional core power distributions which reflect a variety of plant operating conditions. The uncertainty analyses are performed by comparing the 3-dimensional peak factor, Fq and DNB-OPM obtained from MASTER code to those calculated by the off-line SCOPS/SCOMS. The Fq and DNB-OPM modeling uncertainties are statistically combined with other uncertainties. Approximately 1000 cases of axial power distributions at each of three burnup (BOC, MOC, and EOC) are used in the determination of the overall uncertainty factors. These cases are chosen to encompass steady state and quasi-steady state plant operating conditions throughout the cycle lifetime. Axial power distributions are generated by changing the power levels, CRA configurations and xenon and iodine concentrations.

2.2 LPD Statistical Method

The SCOPS/SCOMS synthesized Fq is compared with that of the reactor core simulator. The Fq modeling error, ${E_F}^I$ between SCOPS/SCOMS synthesized Fq and MASTER calculated actual Fq is defined as:

$$ {E_F}^I = \frac{(F_Q^{SYN})^I}{(F_Q^{ACT})^I} - 1 \qquad (1)$$

where, $(F_Q^{SYN})^I$ = Synthesized Fq for i-th case
$(F_Q^{ACT})^I$ = Simulator Fq for i-th case

The Fq error is analyzed for each case at each time-in-life. The mean Fq error, $\overline{E}_F$ and standard deviation of the Fq error, S_F can be calculated from next equations.

$$ \overline{E}_F = \frac{1}{N}\sum_{I=1}^{N} E_F^I \qquad (2)$$

$$ S_F = \left[\frac{1}{N}\sum_{I=1}^{N}\left(E_F^I - \overline{E}_F\right)^2\right]^{1/2} \qquad (3)$$

Since the mean and standard deviation are estimated from the data, the one-sided tolerance limit can be constructed from the k factor. A normality test of the error distribution is performed by using D-prime statistic value to justify the assumption of a normal distribution. If the error is not normally distributed, one-sided 95/95 tolerance limits are calculated by using non-parametric technique based on order statistics and the binomial probability distribution. The error distribution is ordered from the smallest value to the largest value and locator L is calculated form the following equation.

$$ L = Np \pm k \cdot \{Np(1-p)\}^{1/2} \qquad (4)$$

where, p = probability (p=0.05 for upper 95/95)
k = one-sided tolerance limit factor based on normal approximation of the sample standard deviation

The one-sided 95/95 tolerance limit is obtained by selecting the error value from the ordered error distribution corresponding to the location L.

2.3 DNBR Statistical Method

The 3-dimensional reactor core simulator provides a hot-pin power distribution for its DNB-OPM calculation and the corresponding incore and excore detector signals for power distribution algorithm. Reference

DNB-OPM is performed with the fast running DNBR calculation code, FAST. The system temperature, pressure and flow rate are randomly sampled for both the reactor core simulator and SCOPS/SCOMS. In addition, the measurement error of each of these state parameters is randomly sampled and then added to the selected parameters. DNB-OPM modeling error for each case can get as like as Eq. 1. Each error distribution is tested for normality and the mean DNB-OPM error, standard deviation and one-sided 95/95 tolerance limit are computed.

2.4 Uncertainty Components Combining Method

The uncertainties involved in the statistical combination of uncertainty (SCU) method are divided into two categories. The first category, referred to as "system parameter" uncertainties, includes fuel rod/clad uncertainties, CHF correlation uncertainty, thermal-hydraulic code modeling uncertainty. These uncertainties are statistically combined to determine a limit DNBR which ensure that DNBR in the limiting channel will be maintained such that there is at least a 95% probability, with 95% confidence, DNB is avoided.

The second category, referred to as "state parameter" uncertainties, includes measured state parameters, radial peaking factor measurement, simulator model and computer processing uncertainties. The state parameters, algorithm and measurement uncertainties are stochastically simulated to generate a state parameter pdf. The 95/95 probability/confidence level of this function is then root-sum-squared with the other uncertainties to determine the SCOPS/SCOMS overall uncertainty factors. Then resultant uncertainties of the two groups are effectively combined in a deterministic manner. Systematic diagram for uncertainty analysis in order to determine these overall uncertainty factors is illustrated in Fig. 1.

Table 1. Uncertainty Components Used in Uncertainty Analysis

A. Statistically Combined in Min. DNBR Limit - Inlet flow distribution uncert. - Enthalpy rise factor uncert. - Systematic fuel rod pitch uncert. - Systematic fuel clad O.D uncert. - Heat flux factor - CHF correlation uncert. - TH computer code uncert.
B. Modeled Explicitly in SCU - CRA position measurement uncert. - Incore and Excore detector measurement uncert. - Core inlet temperature measurement uncert. - Primary coolant pressure measurement uncert. - Primary coolant flow rate measurement uncert. - Power distribution algorithm modeling uncert. - Thermal-hydraulic algorithm modeling uncert. - Rod shadowing factor measurement uncert. - SAM/BPPCC measurement uncert.
C. Applied Statistically to Uncertainty Factor - Radial peaking factor measurement uncert. - Fuel and poison rod bow penalty - Computer processing uncert. - Reactor core simulator modeling error - LPD engineering factor

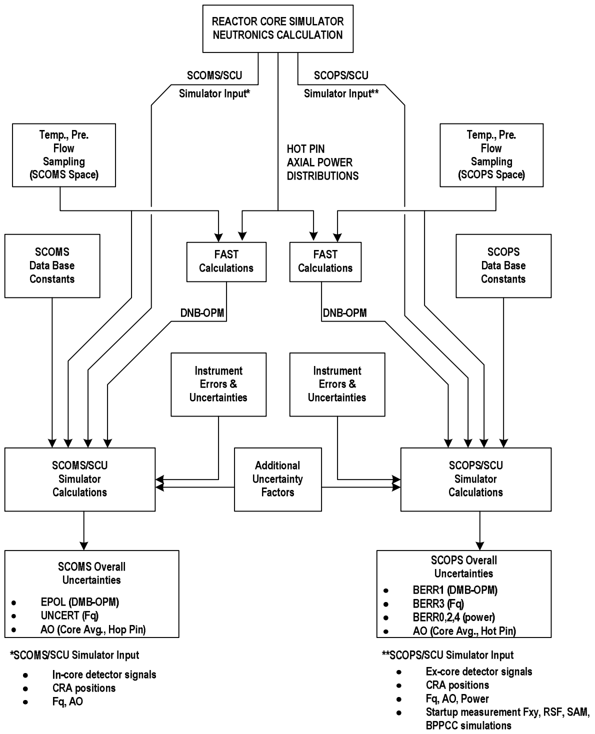

Figure 1. Systematic Diagram for Uncertainty Analysis

3. Conclusions

The technically reliable uncertainty analysis method for SMART digital core protection and monitoring system was developed. The overall uncertainty factors calculated by the method are applied to the on-line DNBR and LPD calculation. This assures that calculated DNBR and LPD are conservative with a 95/95 probability/confidence level.

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