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Thermal Margin Budgets in the Analog/Digital Core Protection and Monitoring Systems

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Abstract

The core thermal margins of the analog/digital core protection and monitoring systems were assessed for Yonggwang units 3-4 and SMART. The setpoints associated with the analog (OPΔT /OTΔT trip function) and the digital systems were determined using the design data of each plant. Following the standard procedure for core thermal margin assessment, the net DNB and LPD overpower margins were estimated and compared for each plant with the analog or digital systems. It was found that the DNB overpower margin is more limiting than the LPD overpower margin for both the protection systems and plants. The limiting DNB overpower margins of the digital core protection system are greater than those of the analog system by 7.5% and 11.1% of rated power for Yonggwang units 3-4 and SMART, respectively.

1. Introduction

The designs of the monitoring and protective systems are integrated with the plant technical specifications (in which operating limits and limiting conditions for operation are specified) to assure that all safety requirements are satisfied. The plant monitoring systems, protection systems and technical specifications thus complement each other. Protection systems provide automatic action to place the plant in a safe condition should an abnormal event occur. The technical specifications set forth the allowable regions and modes of operation on plant systems, components and parameters. The monitoring systems (meters, displays, and systems) assist the operation personnel in enforcing the technical specification requirements. Making use of the monitoring systems, protection system and technical specifications in the manner described above will assure that if, (1) the operating personnel maintain all protective systems settings at or within allowable values, (2) the operating personnel maintain actual plant conditions within the appropriate limiting conditions for operation, and (3) equipment other than that causing an abnormal event or degraded by such an event operates as designed, then all anticipated operational occurrences or postulated accidents will result in acceptable consequences.

The existing pressurized water reactors of Korea were mostly designed by Westinghouse and ABB-CE. Westinghouse employs analog protection and monitoring systems at Kori units 1-4 and Yonggwang units 1-2. The thermal overpower and overtemperature ΔT (OPΔT and OTΔT) protection system[1] is used to provide analog protection against fuel centerline melting and DNBR at the Westinghouse plants. The axial offset band is also set at the analog plants to limit the axial asymmetry of the power distribution, thereby limiting the three-dimensional peaking factor. ABB-CE developed the digital computer based reactor protection and monitoring systems that are used at Yonggwang units 3-4 and Ulchin units 3-4. The Core Protection Calculator Systems (CPCS)[2] provide reactor protection functions by calculating real-time values of DNBR and local power density (LPD) based on live sensor signals. Complementing the CPCS is the Core Operating Limit Supervisory System (COLSS)[3] that calculates the operating margin available at the current plant conditions and provides alarms when technical specification limits are reached.

This study performed a thermal margin assessment for the OPΔT and OTΔT protection systems and the CPCS/COLSS at Yonggwang Units 3-4 and SMART (System-integrated Modular Advanced ReacTor). The thermal margin estimation for Yonggwang Units 3-4[4] is reviewed and updated by examining the thermal margin budget. The setpoints analysis for the SMART OPΔT and OTΔT trip functions and digital systems were carried out and their thermal margins were compared where applicable.

2. System Descriptions

2.1 Digital Plants

ABB-CE digital plants are equipped with both in-core and ex-core detector systems. The ex-core detectors are safety grade and are configured as four independent channels, each containing a 3-level detector string. Each independent channel corresponds to one of the four CPC channels and one of the four nuclear power channels of the reactor protection system. The in-core detectors are configured as 5-level self-powered Rhodium detector strings with a total of 44 to 61 strings, depending on the plant. The in-core detector signals are sent to the plant computer in which they are compensated for both detector depletion and gamma background effects. The raw and compensated in-core signals are then used in COLSS.

The digital core protection system CPCS is comprised of four CPCs and two CEACs. Each CPC provides the low DNBR and local power density trips to assure that the specified acceptable fuel design limits on the departure from nucleate boiling and centerline fuel melting are not exceeded during Anticipated Operational Occurrences (AOO), and to assist the Engineered Safety Features System in limiting the consequences of certain postulated accidents. CPC meets additional design bases via auxiliary trip functions. CPC computes the core average axial power distribution, pseudo hot pin power distribution, and the three dimensional power peak from the ex-core detector signals and target CEA positions. Each CEAC (CEA Calculator) scans all CEA positions to calculate the single CEA position-related penalty factors that are transmitted to the CPCs to be included in the DNBR and LPD calculations. Figure 1 illustrates the CPCS configuration.

COLSS is an on-line digital core monitoring system for the ABB-CE digital plants implemented into the Plant Monitoring System (PMS) that aids the operator in maintaining plant operation within selected Limiting Conditions for Operation (LCOs) such as the DNBR margin, linear heat rate margin and axial shape index, etc. COLSS also computes the core average axial power distribution, pseudo hot pin power distribution, and the three dimensional power peak from the in-core detector signals and target CEA positions. COLSS also provides the calculated value of plant power for comparison to the licensed plant power and is the surveillance reference used to verify proper operation of the CPCS. A major difference between COLSS and the CPCS is that COLSS bases its calculations on signals from the fixed in-core detector system rather than the ex-core detector system.

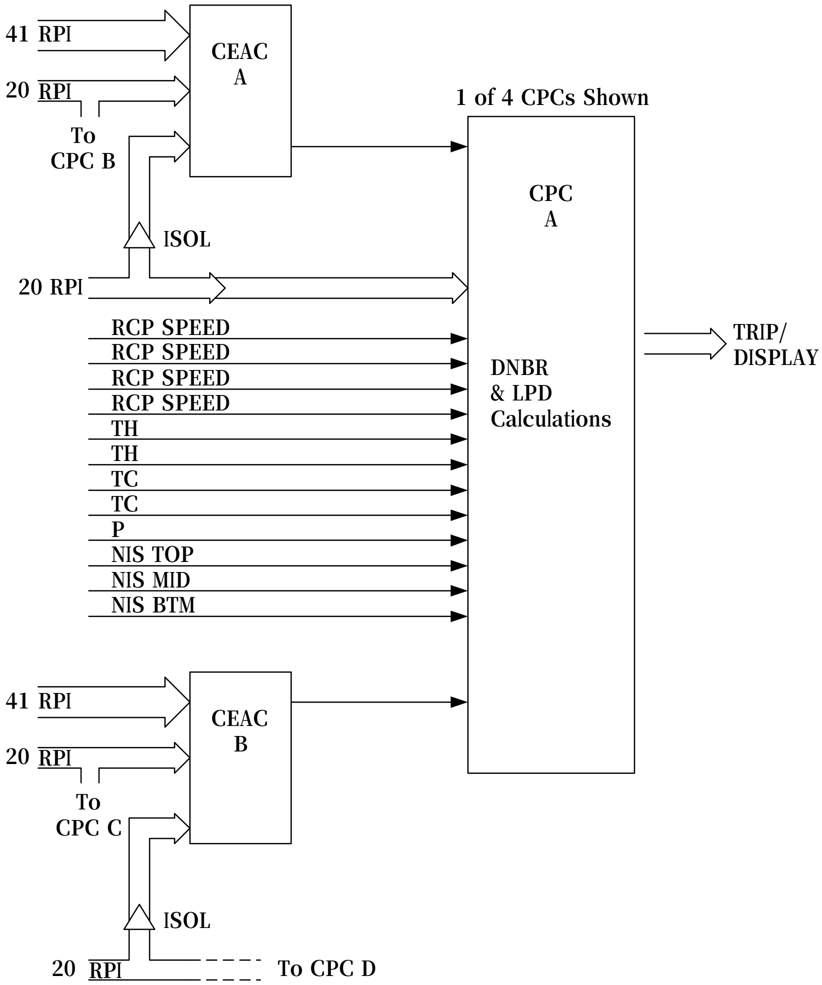

Fig. 1. Digital core protection system CPCS configuration

2.2 Analog Plants

Analog plants are equipped with both in-core and ex-core detector systems in a manner similar to digital plants. The ex-core detectors are safety grade and are configured as four independent channels, each containing a 2-level detector string. Each independent channel corresponds to one of the four nuclear power channels of the reactor protection system. The in-core detectors are configured as either 4 or 5–level detector strings (ABB-CE analog plants) or a single movable string (Westinghouse plants). Trip functions provided by the reactor protection system at an analog plant are similar to the non-digital (non-CPCS) trip functions. In addition, the Westinghouse analog plants have OPΔT and OTΔT trips which correspond to the CPCS trips on LPD and DNBR. Figure 2 shows the schematic diagram of OPΔT and OTΔT protection.

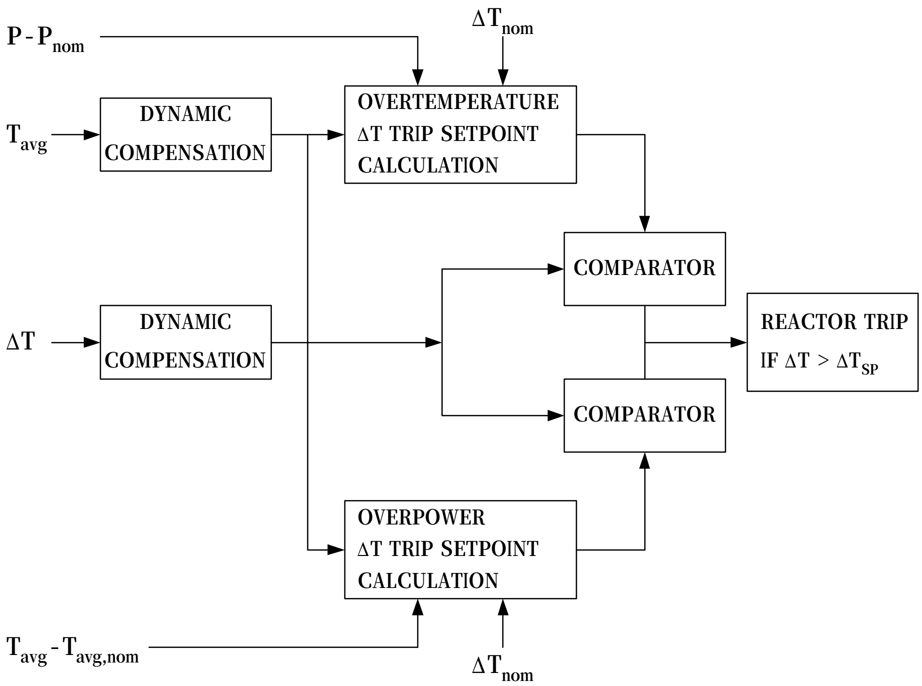

Fig. 2. Schematic diagram of OPΔT and OTΔT protection

The overpower ΔT trip (OPΔT) provides protection against exceeding fuel rod design limits for accidents involving overpower excursions. For normal operation, the temperature rise through the reactor vessel (ΔT) is approximately proportional to power. There is, however, a slight dependence on pressure and reactor inlet temperature due to the change in the density and heat capacity of the water. The overtemperature ΔT trip (OTΔT) protects the core against DNB for any combination of power, pressure, temperature, and axial core power distributions. The thermal hydraulic core limits are provided as a series of lines, each drawn for a different pressure on a core inlet temperature versus power coordinate system. The system used for protection is the coordinate conversion of the core limits to $\Delta T - T_{avg}$ space. The actual ΔT is continuously monitored and compared to the computed ΔT setpoints to actuate a reactor trip as shown in Fig. 2.

There is no separate core monitoring system like COLSS at the Westinghouse analog plants. They monitor the separate state parameters such as pressure, temperature and axial offset (AO) instead of directly checking LHR and DNBR. The axial offset is calculated from the ex-core detector readings and is checked against its allowable band during normal operation and load following maneuvers. The state parameters related to DNBR or LHR are statistically treated in the design process of determining the design safety analysis limit DNBR.

3. Setpoints Analysis

3.1 Limit DNBR and LPD

The limit DNBR for the analog system is calculated by

$$DNBR_{\lim it} = \frac{DNBR_{correlation}}{1 - Ks_{DNBR}} . \quad (1)$$

The symbol K is the 95/95 probability/confidence factor for a one-sided tolerance limit and $DNBR_{correlation}$ is the CHF correlation limit DNBR. The DNBR uncertainty (s_{DNBR}) is calculated by the system moment method as follows.

$$s^2_{DNBR} = \sum_i S_i^2 \left(\frac{s_i}{m_i} \right)^2 . \quad (2)$$

Where

S_i = DNBR sensitivity for parameter i

m_i, s_i = Mean and standard deviation of parameter i

The DNBR sensitivities and the parameter's uncertainty data for Yonggwang units 3-4 are presented in reference [4]. The calculated DNBR uncertainty (s_{DNBR}) is 0.0655 and the CHF correlation (CE-1) limit DNBR for Yonggwang units 3-4 is 1.19. From eq. (2), the limit DNBR for Yonggwang units 3-4 with an OTΔT/OPΔT protection system is calculated as 1.34. Applying the additional penalties for the rod bow (1.8%) and HID grid (1%) gives the final limit DNBR of 1.38 (=1.34*1.018+0.01). The DNBR sensitivities for SMART were computed by the thermal-hydraulic design code (MATRA[5]) with the SR-1 CHF correlation[6]. The parameter's uncertainty data for Yonggwang units 3-4 were assumed to be applicable for SMART. Table 1 lists the calculated DNBR sensitivities and the uncertainty data for SMART. The above system moment method was used to obtain the limit DNBR of 1.53 for the analog system.

The limit DNBR for the digital system is determined by statistically combining the "system" parameter's uncertainties such as the core inlet flow distribution uncertainties, enthalpy rise factor, systematic pitch and clad O.D. uncertainties, CHF correlation uncertainty, code uncertainty, etc. The fuel rod bow penalty and the HID-1 grid penalty are applied deterministically. The calculated limit DNBR for Yonggwang units 3-4 with CPCS/COLSS is 1.30. Similarly, the limit DNBR for the SMART digital system is 1.41.

The LPD limit to avoid PWR fuel centerline melting is 21 kW/ft (689 W/cm). Westinghouse believed that the design basis for fuel melting prevention be satisfied by limiting the core power 118% of rated power for PWR plants. This value (118%) is the basis of the overpower ΔT trip setpoint for Yonggwang units 3-4. However, the limiting core overpower for SMART is assumed to be 135% of rated power by comparing the core average LPD and the 3-D power peaking factor to those of commercial PWR plants. The digital protection system of ABB-CE calculates LPD on-line from the measured power distribution and directly compares it (after the uncertainty correction) to the LPD limit.

Table 1. DNBR sensitivities and parameter's uncertainty for SMART

Parameters	Sensitivity factor	Nominal (m)	Uncertainty (s)
Core flow rate	1.43	1.0	0.025
Core avg. heat flux	–2.18	1.0	0.01
Core inlet temperature	-4.16	270	0.83
Primary pressure	0.89	150	2.07
Nuclear enthalpy rise hot channel factor	-1.97	1.60	0.04
Engineering enthalpy rise hot channel factor	-0.50	1.0	0.015
Engineering heat flux hot channel factor	-1.0	1.0	0.015
TH code		1.0	0.025

3.2 OPΔT and OTΔT Trip Setpoints

The overpower ΔT trip setpoint (excluding the compensation term for the piping and instrument time delay) is

$$OP\Delta T_{SP} = \Delta T\, K_4 \quad \textbf{for} \;\; T_{avg} \le T_{avg,nom} \tag{3}$$

$$OP\Delta T_{SP} = \Delta T\left[K_4 - K_6\left(T_{avg} - T_{avg,nom}\right)\right] \quad \text{for} \quad T_{avg} > T_{avg,nom}\,. \tag{4}$$

Where

ΔT = Indicated temperature rise through the reactor vessel

T_{avg} = Average temperature

$T_{avg,nom}$ = Nominal T_{avg} at rated power

K_4 = Preset manually adjustable bias

K_6 = Constant

The overtemperature ΔT trip setpoint (neglecting the instrument time delay) is

$$OT\Delta T_{SP} = \Delta T\left[K_1 - K_2\left(T_{avg} - T_{avg,nom}\right) + K_3\left(P - P_{nom}\right) - f(\Delta I)\right]. \tag{5}$$

Where

K_1 = Preset manually adjustable bias

K_2 & K_3 = Preset manually adjustable gains

$f(\Delta I)$ = Axial offset penalty

Following the procedure in reference [1], the coefficients of the ΔT trip setpoints are computed for Yonggwang (YGN) units 3-4 and SMART, and their values are summarized in Table 2. The OPΔT and OTΔT trip lines for SMART are shown in Fig. 3. It should be noted that the 1.55 chopped cosine axial power shape and the steady-state design power peak (F_q=2.48) were used to generate the OPΔT and OTΔT trip lines for SMART.

Table 2. Coefficients of OTΔT/OPΔT trip setpoints

Plant	K_1^*	K_2	K_3	K_4^*	K_6
YGN 3/4	1.105	0.01209 (/^{0}F)	0.00089 (/psi)	1.107	0.00306 (/^{0}F)
SMART	1.316	0.0268 (/^{0}C)	0.0149 (/bar)	1.411	0.0038 (/^{0}C)

* Setpoint uncertainty is included; 5.48% for OPΔT trip (K_4) and 5.96% for OTΔT trip (K_1).

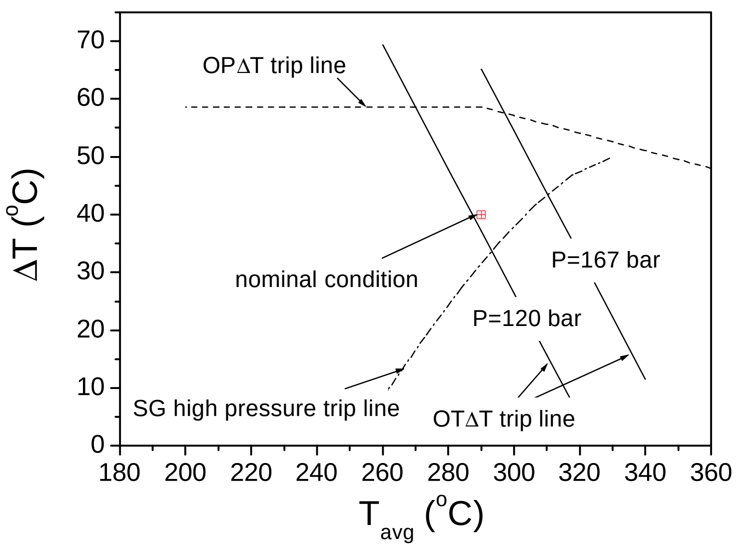

Fig. 3. SMART OPΔT and OTΔT trip limit lines

3.3 Setpoints in Digital Systems

Statistical Combination of Uncertainties (SCU) method is applied to the determination of the Limiting Conditions for Operation (LCO) and Limiting Safety System Setpoints (LSSS) on DNBR and LPD. The overall uncertainty factors for digital core monitoring and protection systems are determined at least at a 95/95 probability/confidence level. The previous SCU method[7] stochastically combines the measurement uncertainties of the “state” parameters such as core inlet temperature, primary coolant pressure, primary coolant flow rate, radial peaking factor, etc. In the Modified SCU methodology[8], the uncertainties of the “state” parameters and the “system” parameters are statistically combined by including the “system” parameter uncertainty DNBR pdf in the overall uncertainty factor calculations via stochastic simulation. The calculated overall uncertainty factors for Yonggwang units 3-4 cycle 1 are listed in Table 3. Since the uncertainty data for SMART are not available, the YGN values are assumed to be applicable to the thermal margin assessment for SMART by engineering judgment.

Table 3. Overall uncertainty factors for the digital protection and monitoring systems

System	Parameter	Value
Protection system (CPCS)	Multiplicative DNBR penalty factor (BERR1) Additive DNBR penalty factor (BERR0, BERR2) Multiplicative LPD penalty factor (BERR3) Additive LPD penalty factor (BERR4)	1.08 3.5%, 2.5% 1.18 12.0%
Monitoring system (COLSS)	Multiplicative DNBR penalty factor (1+EPOL2) Multiplicative LPD penalty factor (UNCERT) Additive power measurement uncertainty for DNBR Additive power measurement uncertainty for LPD	1.05 1.12 0.0 2.0%

4. Thermal Margin Assessment

Analog systems (OP ΔT /OT ΔT trip systems)

Since the thermal margins for the ΔT trip systems are defined as the overpower margin relative to the hot full power (HFP) without the axial offset penalty, the ΔT trip setpoints in eqs. (4) and (5) can be expressed as a fraction of the full-power ΔT (ΔT_{nom}), i.e.,

$$\frac{OP\Delta T_{SP}}{\Delta T_{nom}} = K_4 - K_6\left(T_{avg} - T_{avg,nom}\right) \tag{6}$$

$$\frac{OT\Delta T_{SP}}{\Delta T_{nom}} = K_1 - K_2\left(T_{avg} - T_{avg,nom}\right) + K_3\left(P - P_{nom}\right). \tag{7}$$

At the reactor trip condition, the core average temperature can be written as

$$T_{avg} = T_{in} + \frac{\Delta T_{SP}}{2}. \tag{8}$$

The overpower margins of the OPΔT and OTΔT trip systems can be obtained by inserting eq. (8) into eqs. (6) and (7) along with the constant core inlet temperature and RCS pressure.

For Yonggwang units 3-4, the nominal core inlet temperature (T_{in}) and RCS pressure (P_{nom}) are 564.5 °F and 2250 psia. The nominal temperature rise through the reactor vessel (ΔT_{nom}) is 56.5 °F.

Hence, the nominal core average temperature ($T_{avg,nom}$) can be calculated as 592.75 °F. The estimated overpower margins for YGN units 3-4 are 110.1% for the overpower ΔT trip (LPD protection) and 107.9% for the overtemperature ΔT trip (DNBR protection).

For SMART, the nominal core inlet temperature (T_{in}) and RCS pressure (P_{nom}) are 270 °C and 150 bar. The nominal temperature rise through the reactor vessel (ΔT_{nom}) is 40 °C. Hence, the nominal core average temperature ($T_{avg,nom}$) can be calculated as 290 °C. The estimated net overpower margins for SMART are 138.2% for the overpower ΔT trip (LPD protection) and 120.6% for the overtemperature ΔT trip (DNBR protection).

Digital core protection and monitoring systems

The thermal margins for the core digital protection and monitoring systems are estimated based on the available overpower margin (AOPM) and the overall uncertainty (process uncertainty and instrumentation uncertainty) of each system. Figure 4 illustrates the DNB overpower margin budget of the digital core protection and monitoring systems. The available DNB overpower margin for Yonggwang units 3-4 was calculated at the nominal core inlet temperature and RCS pressure, the best estimate core flow rate (107.5% design), and the design core axial and radial power distributions. The calculated AOPM values for Yonggwang units 3-4 cycle 1 are 142.5% (BOC), 134.1% (MOC), and 138.6% (EOC). Similarly, the available DNB overpower margins for SMART are 159.9% (BOC), 161.3% (MOC), and 153.0% (EOC). The minimum measured core flow rate (105% design) was conservatively used to calculate the DNB AOPM for SMART. Figure 5 shows the design axial power shapes at BOC, MOC, and EOC of Yonggwang units 3-4 cycle 1 and SMART. The net DNB overpower margins are calculated following the standard procedure as in Table 4. The LPD margins of the digital protection and monitoring systems are calculated from the LPD limits for fuel centerline line melting (or LCO) and the cycle maximum 3-D power peak (F_q). Table 5 shows the calculations of the net LPD margins.

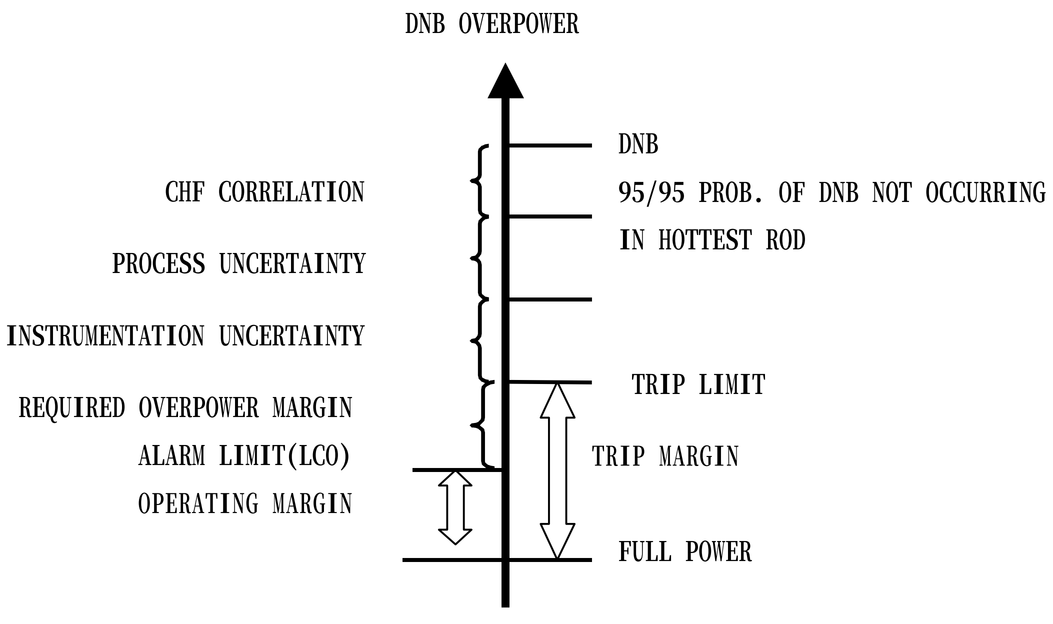

Fig. 4. DNB overpower margin budgets of the digital core protection and monitoring systems

The net DNB and LPD overpower margins of the analog and digital core protection systems are compared in Table 6. For both analog and digital systems, the DNB overpower margin (DNB-OPM) is less than the LPD overpower margin (LPD-OPM) for Yonggwang units 3-4 and SMART. The LPD-OPM of the analog system is significantly less than that of the digital system because the analog protection system (OPΔT) uses an overly conservative limiting thermal overpower for fuel melting protection. The limiting DNB-OPMs of the digital core protection system are greater than those of the analog system by 7.5% (Yonggwang units 3-4) and 11.1% (SMART) of rated power. The DNB margin gains of the digital system are largely due to the direct calculation of DNBR based on the measured core axial power shape and core flow rate, while the analog DNB protection system conservatively uses the 1.55 chopped cosine axial shape and the thermal design flow rate.

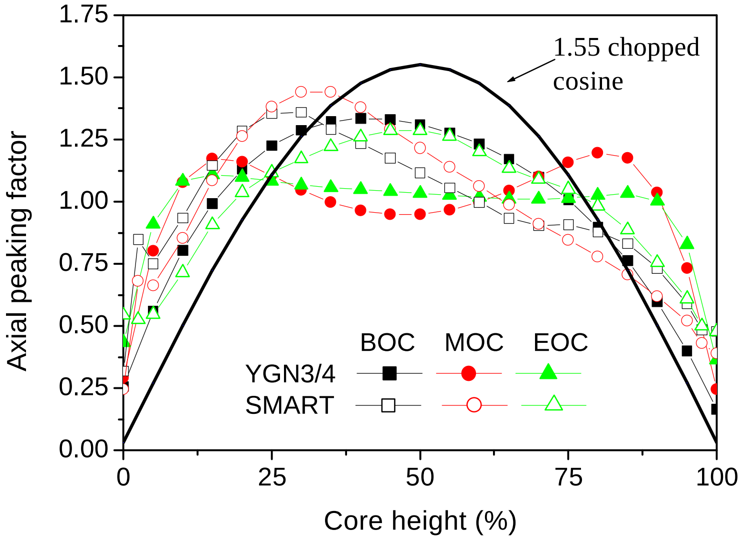

Fig. 5. Core axial power distributions for Yonggwang units 3-4 cycle 1 and SMART

Table 4. DNB overpower margins of digital core protection and monitoring systems

Parameters	Penalty	Digital protection YGN 3/4	Digital protection SMART	Digital monitoring YGN 3/4	Digital monitoring SMART
DNB AOPM (% of rated power)		134.1	153.0	134.1	153.0
Overall uncertainty factor					
- BERR1 (/)	1.08	124.2	141.2		
- 1+EPOL2 (/)	1.05			127.7	145.7
Required OPM for AOOs (/)					
- YGN 3/4	1.16			110.1	
- SMART	1.14				127.8
Tilt allowance (/)					
- Protection system	1.015	122.4	139.1		
- Monitoring system	1.01			109.0	126.5
Power meas. Uncertainty (-)					

- Max(BERR0, BERR2) Operational allowance (/)	3.5 1.03	118.9 115.4	135.6 131.7	 105.8	 122.8
Minimum net DNB-OPM (% of rated power)		115.4	131.7	105.8	122.8

Table 5. LPD overpower margins of digital core protection and monitoring systems

Parameters	Penalty	Digital protection YGN 3/4	Digital protection SMART	Digital monitoring YGN 3/4	Digital monitoring SMART
F_q		2.0	2.3	2.0	2.3
LPD AOPM* (% of rated power)		194.7	245.3	128.9	N/A
Overall uncertainty factor (/)					
- BERR3	1.18	165.0	207.9		
- UNCERT	1.12			115.1	N/A
Tilt allowance (/)					
- Protection system	1.015	162.6	204.8		
- Monitoring system	1.01			114.0	N/A
Power meas. uncertainty (-)					
- BERR4	12.0	150.6	192.8		
- Monitoring system	2.0			112.0	N/A
Operational allowance (/)	1.03	146.2	187.2	108.7	N/A
Minimum net LPD-OPM (% of rated power)		146.2	187.2	108.7	N/A

* LPD AOPM (% of rated power) = 100*LPD limit (or LCO) / (F_q * q_{avg})
where LPD limit = 21 kw/ft (689 W/cm), LPD(LCO)=456 W/cm for YGN3/4
and q_{avg}=176.9 W/cm (YGN3/4), 122.1 W/cm (SMART).

Table 6. Comparisons of the thermal margins for analog and digital core protection systems

Overpower margins	YGN 3/4 Analog	YGN 3/4 Digital	SMART Analog	SMART Digital
Minimum net DNB-OPM (% of rated power)	107.9	115.4	120.6	131.7
Minimum net LPD-OPM (% of rated power)	110.1	146.2	138.2	187.2

5. Conclusion

This study estimated the core thermal margins (DNB-OPM and LPD-OPM) of the analog/digital protection and monitoring systems for Yonggwang units 3-4 and SMART. The thermal margin budget of each case was evaluated using the design data, and the net margins to reactor trip and LCO were then calculated. The DNB overpower margin (DNB-OPM) is less than the LPD overpower margin (LPD-OPM) for both analog and digital systems at Yonggwang units 3-4 and SMART. The minimum net LPD-OPM of the digital protection system is greater than that of the analog system (OPΔT) by at least 30% of rated power. This is mainly due to the use of the excessively conservative limiting thermal overpower in the OPΔT trip setpoint. The minimum net DNB-OPMs of the digital core protection system are greater than those of the analog system by 7.5% (Yonggwang units 3-4) and 11.1% (SMART) of rated power. The DNB margin gains of the digital system are largely due to the direct calculation of DNBR in the digital system using the measured core axial power shape and core flow rate.

Acknowledgements

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References

[1] S.L. Ellenberger, *et al.*, “Design Bases for the Thermal Overpower ΔT and Thermal Overtemperature ΔT Trip Functions,” WCAP-8746, March, 1977.

[2] C.R. Musick, “Method and Apparatus for Controlling a Nuclear Reactor,” US Patent #4,318,778, March, 1982.

[3] C.R. Musick, “Method and Apparatus for Controlling a Nuclear Reactor,” US Patent #4,080,251, March, 1978.

[4] G.S. Auh, D.H. Hwang, S.H. Kim, “A Steady-State Margin Comparison between Analog and Digital Protection Systems,” J. of the KNS, Vol. 22, No. 1, pp. 45-57, 1990.

[5] Y.J. Yoo and D.H. Hwang, “Development of a Subchannel Analysis Code MATRA,” KAERI/TR-1033/98, April, 1998.

[6] 황대현, 유연종, 지성균, “SMART 노심조건에 대한 국부조건 CHF 상관식 개발,” 2000 춘계학술발표회 논문집, 한국원자력학회, 2000.

[7] Combustion Engineering Inc., “Statistical Combination of Uncertainties for Waterford-3,” CEN-343(C)-P, October, 1986.

[8] Combustion Engineering Inc., “Modified Statistical Combination of Uncertainties,” CEN-356(V)-P-A, Rev. 01-P-A, May, 1988.