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A Study on the Enhancement of Westinghouse DNB Protection Logic

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Abstract

Since the conventional Westinghouse DNB (Departure from Nucleate Boiling) protection logic is implemented on analog circuits, the logic must be very simple. However, if the DNB protection logic is implemented in a digital processor, a little bit of complexity can be allowed to increase the thermal (or operation) margin. The Westinghouse $OT\Delta T$ DNB protection logic heavily restricts the operation region by applying the same logic for a full range of pressure in order to maintain its simplicity. In this work, the different DNB protection logic is used for several regions of pressure. The proposed method is applied to Yonggwang 1 & 2 nuclear power plants and it is calculated that the improved $OT\Delta T$ can have 5.07% percent more thermal margin than the conventional $OT\Delta T$ trip logic.

1. Introduction

The protection system of the conventional pressurized water reactor designed by Westinghouse is an analog system. However, the Korea Standard Nuclear Power Plant (KSNPP) and the currently designed nuclear reactors employ a digital protection system. The CE-type nuclear power plants which KSNPP is based on, employ the Core Protection Calculator System (CPCS) which continuously calculate DNBR and Local Power Density (LPD) in order to assure that the specified acceptable fuel design limits on DNB and centerline melt are not exceeded during anticipated operational occurrences. The CPCS has approximately 6,000 constants and the CPCS is designed by deciding the CPCS constants[1]. This large number of constants makes the software V&V (Verification and Validation) more difficult.

Since the conventional Westinghouse DNB protection logic is implemented on analog circuits, the logic must be very simple. The Westinghouse $OT\Delta T$ protection logic heavily restricts the operation region by applying the same logic for a full range of pressure in order to maintain its simplicity. However, if the DNB protection logic is implemented in a digital processor, a little complexity can be allowed to increase the thermal (or operation) margin.

The objective of this work is to improve the DNB protection logic based on the $OT\Delta T$ trip logic by using the different DNB protection logic for several regions of pressure in order to increase the thermal margin. Instead of a dynamic thermal margin, a steady-state thermal margin is compared between the conventional DNB protection system and the proposed one because their dynamic terms will be made to be same.

2. $OT\Delta T$ Trip Logic

Since this work is based on the DNB protection logic of Westinghouse, the $OT\Delta T$ trip logic will be described. The Westinghouse DNB protection is accomplished by the trip circuit automatically comparing the reactor ΔT (temperature difference between the hot-leg and the cold-leg) to a constantly recalculated ΔT setpoint ΔT_{sp}. ΔT_{sp} is a function of ΔT at rated power and is modified by coolant pressure and temperature and localized flux peaking. $OT\Delta T$ trip logic is as follows:

$$\Delta T_{sp} = \Delta T_o\left[K_1 - K_2\frac{1+\tau_1 s}{1+\tau_2 s}(T_{avg} - T_{avgo}) + K_3(P - P_o) - f(\Delta q)\right]. \tag{1}$$

By the thermal design procedure of Westinghouse [2], the overtemperature ΔT protection limits are determined from DNB limit lines, $OP\Delta T$ limit lines, hot-leg boiling limit lines and steam generator safety valve opening lines and K_1, K_2, and K_3 of $OT\Delta T$ protection logic are determined from four intersection points in Fig. 1. Once the protection limits are calculated from the core limits, instrumentation errors which are not included in the core limits are subtracted from the maximum allowable trip setpoint to yield the nominal setpoint. The protection lines can be derived by adjusting K_1 value so as to include all adverse instrumentation and setpoint errors so that under nominal conditions a plant trip would occur well within the area bounded by these lines.

3. Determination of DNB Protection Limit Lines

The present method of the DNB protection follows the thermal design procedure similar to one developed by Westinghouse. The DNB core limits are the locus of points in core power, inlet temperature T_c, and pressure, along which the minimum DNBR is the design limit DNBR determined from the DNBR sensitivities and variances in three input parameter categories. All input parameters are primarily nominal values except for core power, T_c and RCS pressure, which are varied to determine the points at which the design limit DNBR is obtained. By performing the calculations in this manner, the DNB core limits are mapped in a straightforward manner into reactor coolant ΔT versus T_{avg} space. ΔT is defined as the difference between the hot-leg temperature T_h and the cold-leg temperature T_c and T_{avg} is defined as $(T_c + T_h)/2$ [2]. The lines of constant DNBR are drawn for sixteen different pressures between the high pressure trip setpoint and the low one. The sixteen different pressures are chosen as points divided into a equal interval between the high and low pressure trip setpoints (including these pressure trip setpoints). The sixteen pressures are divided into five groups. Then, each different DNB protection logic is applied for five groups.

The three other limit lines, which complete the definition of an allowable operation region, are: 1) the steam generator safety valve opening line, 2) the overpower ΔT trip line which is plotted directly as the maximum allowable overpower setpoint line, 3) hot-leg boiling limit line which is more restrictive than the DNB limits for low pressure transients.

The overtemperature ΔT equation for each pressure region is calculated from the following points, respectively [3]:

Point A: the intersection point of the 118 percent overpower line and the DNB limit line corresponding to the highest pressure value for each pressure region.

Point B: the intersection point of the 118 percent overpower line and the DNB limit line corresponding to the lowest pressure value for each pressure region.

Point C: the intersection point of the steam generator safety valve opening line and the DNB limit line corresponding to the highest pressure value for each pressure region.

Point D: the intersection point of the steam generator safety valve opening line and the DNB limit line corresponding to the lowest pressure value for each pressure region.

From Eq. (1), for an 1.55 chopped cosine shape at steady-state condition, the $OT\Delta T$ protection limit equation is as follows:

$$\Delta T_{sp} = \Delta T_0[K_1 - K_2(T_{avg} - T_{avg0}) + K_3(P - P_0)]. \qquad (2)$$

The constants K_1, K_2 and K_3 can be determined by solving three simultaneous equations derived from the four intersection points. Each resulting equation is tested for various pressures inside the defined pressure region in order to assure that all the DNB limits are covered. Generally, two of the equations derived from the two intersection points are found to provide protection over each pressure range. The final equation is selected based on maximum available operating margin. The dynamic term and $f(\Delta q)$ term for the flux difference in Eq. (1) are determined by the conventional $OT\Delta T$ protection logic.

The final $OT\Delta T$ setpoint is determined by adjusting K_1 based on appropriate allowances for uncertainties and equipment and measurement errors.

Determination of DNB Limit Lines

The DNB limit lines give the permissible regions of reactor vessel average temperature and ΔT in a two-dimensional plot. As the core power and inlet temperature are varied at the given pressure using thermal-hydraulic analysis computer code of the reactor core, the vessel average hot-leg temperature is read when the minimum DNBR of the limiting power rod is equal to the design limit DNBR under the major assumptions proposed by the Westinghouse thermal design procedure.

Determination of $OP\Delta T$ Limit Lines

As the inlet temperature and the core pressure are varied at 118% of the rated power, the average coolant temperature and ΔT are calculated from the thermal balance equation.

Determination of Hot-Leg Boiling Limit Lines

The hot-leg temperature must be less than the saturation temperature to assure that the vessel average coolant temperature rise ΔT is proportional to core power. As the core heat output and the core pressure are varied with the hot-leg saturated, the average coolant temperature and ΔT are calculated from the thermal balance equation.

Determination of Steam Generator Safety Valve Opening Lines

The steam generator safety valve opens when the steam generator pressure reaches a preset value. Since the reactor operation is limited by opening the steam generator safety valve, the condition of the valve opening needs to be considered in determining the permissible core operation region. The valve opening line can be computed from the fundamental log-mean-temperature-difference equation. lance in the steam generator at the nominal condition.

4. Application to Yonggwang 1&2 Units

In order to calculate quantitatively the thermal margin of the conventional $OT\Delta T$ method and the proposed DNB protection method and to compare their thermal margins, their methods are applied to the first fuel cycle of Yonggwang 1&2 Units.

The design limit DNBR is 1.49 for typical cell of Yonggwang 1&2 units [5] and the design critical heat flux correlation is WRB-1. However, in this work, since COBRA code with W-3 correlation is used for DNBR calculation and the uncertainty of the W-3 is greater than that of WRB-1, the design limit DNBR is assumed to be 1.54 based on reference 2. Other input parameters are considered to be nominal values except for the major assumptions. As the core power and inlet temperature are varied at the given pressure using COBRA code, the vessel average hot-leg temperature is calculated when the minimum DNBR of the limiting power rod is equal to the design limit DNBR. It is known that the overpower ΔT limit lines and the DNB limit lines include the hot-leg boiling limit lines.

For an 1.55 chopped cosine shape at steady-state condition, $OT\Delta T$ trip setpoint is determined from the following data; $T_{avg0} = 310.05^{o}C$, $\Delta T_0 = 36.0^{o}C$, $P_0 = 155.13\,bar$ and the saturated steam generator temperature, $525.7^{o}F$ and the saturated temperature at the opening pressure of a safety valve, $567.22^{o}F$ at the nominal condition. Considering the limit lines, it is known that $OT\Delta T$ setpoint should be determined from points A, C and D given in Sect. 3. The allowable region for each pressure is shown in Fig. 2.

The limit lines for each pressure region are shown in Figs. 3-7, respectively. The pressure regions are divided as follows:

the 1st pressure range: 2400 ~ 2275 psia,
the 2nd pressure range: 2275 ~ 2150 psia,
the 3rd pressure range: 2150 ~ 2025 psia,
the 4th pressure range: 2025 ~ 1900 psia,
the 5th pressure range: 1900 ~ 1775 psia.

From the figures, the constants K_1, K_2, and K_3 are determined and are given in table 1. Then, based on appropriate allowances for uncertainties and equipment and measurement errors, adjusting K_1 is required. Since the typical error allowance for calibration and instrument channel errors is 6.5 percent [2], this error allowance is subtracted from each K_1 value. The adjusted K_1 is given in table 1.

The thermal margin can be defined as $\Delta T_{sp} / \Delta T_0$ when Eq. (2) is satisfied at nominal cold leg temperature and RCS pressure. The nominal cold leg temperature and RCS pressure are $292.06\,^{\circ}C$ and $2250\,psia$. The thermal margin is calculated by substituting the following equation into Eq. (2):

$$T_{avg} = \frac{\Delta T_{sp}}{2} + T_c. \tag{3}$$

Since $(T_{avg} - T_{avg0}) = \frac{\Delta T_0}{2}\left[\frac{\Delta T_{sp}}{\Delta T_0} - 1\right]$, the thermal margin can be calculated as follows:

$$\frac{\Delta T_{sp}}{\Delta T_0} = \frac{K_1 + K_2 \cdot \frac{\Delta T_0}{2}}{1 + K_2 \cdot \frac{\Delta T_0}{2}}. \tag{4}$$

From table 1, the thermal margin of the conventional method is 106.65% and that of the proposed method is 111.72% for Region II.

5. Conclusions

Based on the Westinghouse thermal design procedure, the $OT\Delta T$ protection logic was improved. Although compared to Yonggwang 3&4 units nuclear power plant, the CPCS has about 10 percent more margin at BOC and 2.6 percent more margin at EOC more than the conventional $OT\Delta T$ trip logic [1]. However, if we simply apply the respective different $OT\Delta T$ trip logic for each pressure range, the improved $OT\Delta T$ trip logic has 5.07% percent more thermal margin than the conventional $OT\Delta T$.

Also, since the proposed method is based on the Westinghouse thermal design method, it can easily be applied to the DNB protection system of the Westinghouse-type pressurized water reactor.

Acknowledgements

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Table 1. Comparison of the conventional method and the proposed method

method		three points ($T_{avg}[°C]$, $\Delta T[°C]$, $P[bar]$)	related equations	bias
Conventional method		(316.92, 40.90, 165.47)	$1.136111 = K_1 - 6.87K_2 + 10.3420K_3$	$K_1 = 1.1598$
		(327.02, 32.33, 165.47)	$0.898056 = K_1 - 16.97K_2 + 10.3420K_3$	$K_2 = 0.023570$
		(315.55, 21.32, 122.38)	$0.592222 = K_1 - 5.50K_2 - 32.7496K_3$	$K_3 = 0.013371$
		$K_1 = 1.0948$		
Proposed method	Reg. I	(316.92, 40.90, 165.47)	$1.136111 = K_1 - 6.87K_2 + 10.3420K_3$	$K_1 = 1.2243$
		(327.02, 32.33, 165.47)	$0.898056 = K_1 - 16.97K_2 + 10.3420K_3$	$K_2 = 0.023570$
		(325.72, 31.22, 156.85)	$0.867222 = K_1 - 15.67K_2 + 1.7237K_3$	$K_3 = 0.007133$
		$K_1 = 1.1593$		
	Reg. II	(314.08, 41.30, 156.85)	$1.147222 = K_1 - 4.03K_2 + 1.7237K_3$	$K_1 = 1.2331$
		(325.92, 31.02, 156.85)	$0.861667 = K_1 - 15.87K_2 + 1.7237K_3$	$K_2 = 0.024118$
		(324.72, 30.02, 148.23)	$0.833889 = K_1 - 14.67K_2 - 6.8946K_3$	$K_3 = 0.006581$
		$K_1 = 1.1681$		
	Reg. III	(311.18, 41.73, 148.23)	$1.159167 = K_1 - 1.13K_2 - 6.8946K_3$	$K_1 = 1.2751$
		(324.89, 29.84, 148.23)	$0.828889 = K_1 - 14.84K_2 - 6.8946K_3$	$K_2 = 0.024090$
		(322.58, 27.85, 139.62)	$0.773611 = K_1 - 12.53K_2 - 15.5130K_3$	$K_3 = 0.012871$
		$K_1 = 1.2101$		
	Reg. IV	(308.26, 42.17, 139.62)	$1.171389 = K_1 + 1.79K_2 - 15.5130K_3$	$K_1 = 1.4590$
		(322.68, 27.66, 139.62)	$0.768333 = K_1 - 12.63K_2 - 15.5130K_3$	$K_2 = 0.027951$
		(319.17, 24.44, 131.00)	$0.678889 = K_1 - 9.12K_2 - 24.1313K_3$	$K_3 = 0.021762$
		$K_1 = 1.3940$		
	Reg. V	(305.62, 42.55, 131.00)	$1.181944 = K_1 + 4.43K_2 - 24.1313K_3$	$K_1 = 1.6461$
		(319.25, 24.30, 131.00)	$0.675000 = K_1 - 9.20K_2 - 24.1313K_3$	$K_2 = 0.037193$
		(315.75, 20.90, 122.38)	$0.580556 = K_1 - 5.70K_2 - 32.7496K_3$	$K_3 = 0.026063$
		$K_1 = 1.5811$		

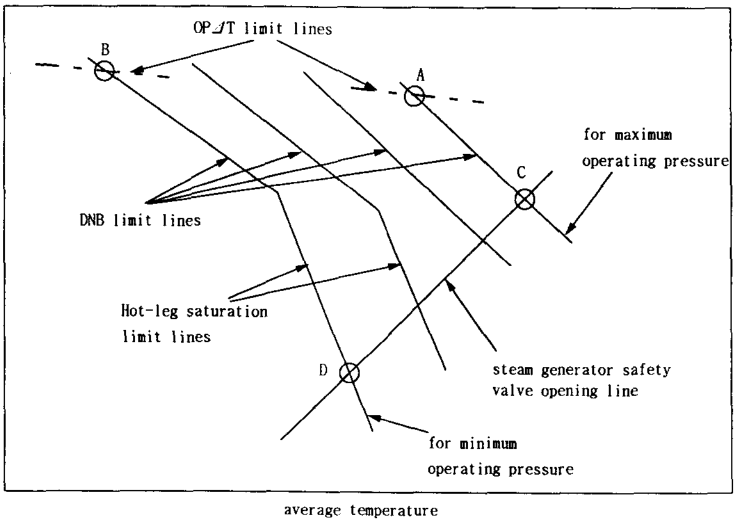

Fig. 1. Protection Limit Lines

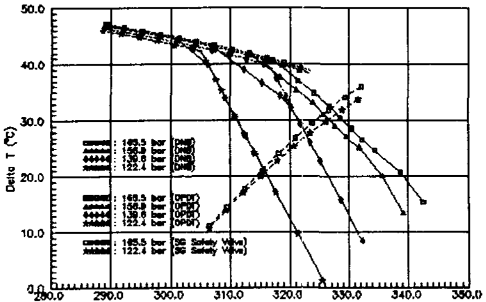

Fig. 2. Overpower DT and Overtemperature DT Protection Lines and SG Safety Valve Opening Lines

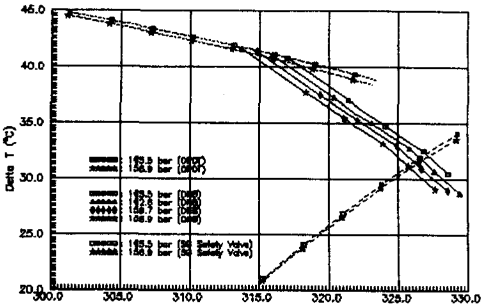

Fig. 3. Overpower DT and Overtemperature DT Protection Lines and SG Safety Valve Opening Lines (Region 1)

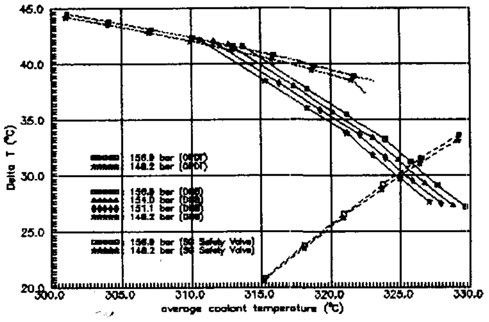

Fig. 4. Overpower DT and Overtemperature DT Protection Lines and SG Safety Valve Opening Lines (Region 2)

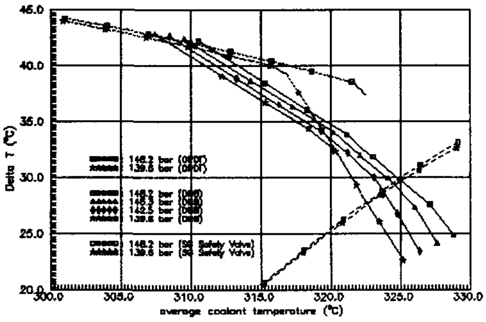

Fig. 5. Overpower DT and Overtemperature DT Protection Lines and SG Safety Valve Opening Lines (Region 3)

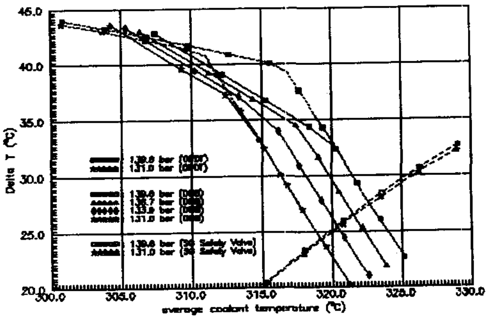

Fig. 6. Overpower DT and Overtemperature DT Protection Lines and SG Safety Valve Opening Lines (Region 4)

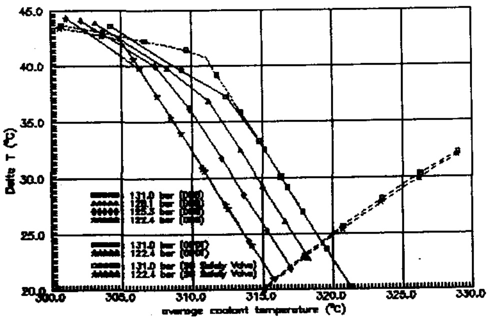

Fig. 7. Overpower DT and Overtemperature DT Protection Lines and SG Safety Valve Opening Lines (Region 5)