

A Steady-State Margin Comparison between Analog and Digital Protection Systems

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아날로그와 디지털 보호계통의 정상 상태 여유도 비교

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Abstract

A steady-state margin comparison study was performed between analog and digital protection systems. The systems compared are the thermal overpower and overtemperature delta T system of Westinghouse, and Core Protection Calculator System of Combustion Engineering, Inc. No dynamic offset was considered to eliminate the margin differences by different safety analysis methodologies. The result shows that the digital protection system has about 30% more rated power margin than the analog system in protecting against the fuel rod centerline melting. The digital protection system is shown to have almost same margin with the analog protection system in preventing the DNB at EOC (End of Cycle) even if the digital protection system has about 10% more margin at BOC (Beginning of Cycle).

요 약

아날로그와 디지털 보호계통의 정상상태 여유도를 비교하였다. 비교된 예는 웨스팅하우스사의 OP Delta T 및 OT Delta T 계통과 CE사의 CPCS 계통이다. 안전해석 방법의 차이에 의한 여유도 영향을 제거하기 위해 Dynamic Offset은 고려하지 않았다. 핵연료봉 중심선의 용융을 방지하는데 있어서 디지털 보호계통이 아날로그 보호계통보다 약 30% 출력 정도의 운전 여유도를 더 가졌다. DNB를 방지하는데 있어서는 주기말에서는 양 보호계통이 비슷한 여유를 가졌으나 주기초에서는 디지털 보호계통이 약 10%의 더 많은 운전여유를 가지는 것으로 판단된다.

1. Introduction

The existing Pressurized Water Reactors (PWR's) of

Korea were largely designed by Westinghouse Electric Company. They employ an analog protection system to prevent Departure from Nucleate Boiling

(DNB). The Yonggwang Nuclear Units 3 and 4 (YGN 3&4) are, however, being designed jointly by Combustion Engineering, Inc. and Korea Atomic Energy Research Institute (KAERI). A digital protection system is used in YGN 3 and 4 to prevent the DNB. Since the reloads of the existing PWR's of Korea are also designed by KAERI, a unique opportunity exists to compare the analog and digital protection systems.

The thermal overpower and overtemperature $\Delta T(OP\Delta T$ and $OT\Delta T)$ system [1] [4] of Westinghouse is used for a typical analog protection system against DNB and fuel centerline melting. And the CPC system [2] [3] of Combustion Engineering, Inc. is used for a typical digital protection system against DNB and fuel centerline melting.

In this study, a steady-state margin was compared between the analog and digital protection systems. This comparison will show the distances between the operating point and the LSSS (Limiting Safety System Setting) for two typical analog and digital protection systems. The concept of steady-state margin is used here instead of operating margin since no dynamic offset was considered to eliminate the margin differences by different safety analysis methodologies (The dynamic offset is used to meet the safety analysis requirements of the limiting transient events). The steady-state margin means that the power difference between the full rated power and the power at which the DNB or the fuel centerline melting occurs when only the core power is increased from the rated power conditions (no dynamics offset, all-rods-out equilibrium power shape at full power, nominal pressure, cold leg temperature and core flow rate). No benefit was taken for plant and core feedback on power shape and pressure.

2. System Descriptions

Functional Description of $OP\Delta T$ and $OT\Delta T$ Systems

The thermal overpower trip is designed to ensure the

operation within the fuel temperature design basis: "during normal operation, operational transients, and transient conditions arising from faults of moderate frequency (ANS Condition I and II events), the uranium dioxide melting temperature shall not be exceeded for at least 95 percent of the limiting fuel rods at a 95 percent confidence level." Experiences with Westinghouse PWRs have shown that this can be accomplished by controlling the gross core thermal power within a prescribed limit (typically 118 percent of nominal power). This is done through the overpower trip by correlating core thermal power with the temperature difference across the vessel (ΔT). Since thermal power is not proportional to ΔT because of the effects of changes in coolant density and heat capacity, a compensating term which is a function of vessel average temperature is factored into the overpower trip setting. Similarly, since the prescribed overpower limit may not be adequate for highly skewed axial power distributions, another compensating term related to the axial flux difference is factored into the overpower trip setting. The thermal overpower protection function will trip the reactor when the compensated ΔT exceeds the setpoint. The steady-state setpoint equation for the thermal overpower protection is:

$$\Delta T_{\text{setpoint}} = K_4 K_6 (T_{\text{avg}} - T_{\text{avg, nom}}) \cdot f(\Delta I) \quad (1)$$

where

$\Delta T_{\text{setpoint}}$ = overpower ΔT setpoint (percent of full-power ΔT)

K_4 = preset manually adjustable bias (percent of full-power ΔT)

K_6 = a constant that accounts for the effects of coolant density and heat capacity on the relationship between ΔT and thermal power (percent of full-power $\Delta T/^\circ\text{F}$).

T_{avg} = average reactor-coolant temperature ($^\circ\text{F}$)

$T_{\text{avg, nom}}$ = nominal average reactor-coolant temperature ($^\circ\text{F}$)

$f(\Delta I)$ = trip reset function of the neutron flux difference between upper and lower half cores (percent of full-power ΔT). Increases in ΔI beyond a predetermined dead band result in a decrease in the trip setpoint.

ΔI = neutron flux difference between upper and lower half cores.

The thermal overtemperature trip is designed to ensure the operation within the hot-leg boiling limit and the DNB design basis: "during ANS Condition I and II events, the probability that DNB will not occur on the limiting fuel rod is at least 95 percent at a 95 percent confidence level." Since both of these limits are function of coolant temperature and pressure as well as core thermal power, the overtemperature trip is correlated with vessel ΔT , core average temperature and primary system pressure. A compensating term which is a function of ΔI is also factored into the overtemperature trip setting to offset the effect of core power distribution on DNB. The thermal overtemperature protection function will trip the reactor when the compensated ΔT exceeds the setpoint. The steady-state setpoint equation for the thermal overtemperature protection is:

$$\Delta T_{\text{setpoint}} = K_1 \cdot K_2 (T_{\text{avg}} - T_{\text{avg, nom}}) + K_3 (P - P_{\text{nom}}) - f(\Delta I) \quad (2)$$

where

$\Delta T_{\text{setpoint}}$ = overtemperature ΔT setpoint (percent of full-power ΔT)

K_1 = a preset, manually adjustable bias (percent of full-power ΔT)

K_2 = a constant based on the effect of temperature on the design limits (percent of full-power $\Delta T/^\circ\text{F}$)

K_3 = a constant based on the effect of pressure on the design limits (percent of full-power $\Delta T/\text{psi}$)

P = pressurizer pressure (psig)

P_{nom} = nominal pressurizer pressure (psig)

Other definitions are same as in equation (1).

Functional Description of CPC System

A CPC (Core Protection Calculator) is one of 4 computers which continuously calculate DNBR and Local Power Density (LPD) to initiate a reactor trip when needed during certain transients to prevent violation

of the DNB and fuel centerline melt fuel design limits. A CEAC (Control Element Assembly Calculator) is one of 2 computers which continuously measure positions of all CEA's (Control Element Assemblies) to detect deviations and provide power penalties, if needed, for input to the CPC's. CPCS (CPC System) is comprised of 4 CPC's and two CEAC's which provides the 4 independent channels for the DNBR and LPD trip functions. The low DNBR and high LPD trips assure that the Specified Acceptable Fuel Design Limits (SAFDL's) on DNB and centerline melt are not exceeded during Anticipated Operational Occurrences (AOO's), and assist the Engineered Safety Features Actuation System (ESFAS) by limiting the consequences of certain postulated accidents. The CPCS software has approximately 6,000 constants. The CPCS design is determined by deciding the CPCS constants. Figure 1 shows a simplified CPCS algorithm diagram.

Statistical Uncertainty Treatments for CPCS

The overall uncertainty analysis establishes that the adjusted LPD and DNBR are conservative at a 95/95 probability confidence level throughout the core cycle with respect to actual core conditions. The CPC uses the plant parameters as input data and calculates the on-line LPD and DNBR. The calculated LPD and DNBR are compared to their respective setpoints and, if necessary, a trip signal is generated. These two protective functions assure safe operation of a reactor in accordance with the criteria established in 10CFR50 Appendix. A. The LSSS (Limiting Safety System Setting) establishes the thresholds for automatic protection system actions to prevent the reactor core from exceeding the SAFDL on centerline fuel melting and DNB, provided that the reactor is operated within the LCO (Limiting Condition for Operation) limits defined by the Tech. Spec.

The probability distribution functions associated with the algorithm and sensor uncertainties are analyzed to obtain the LPD and DNBR overall uncertainty fac-

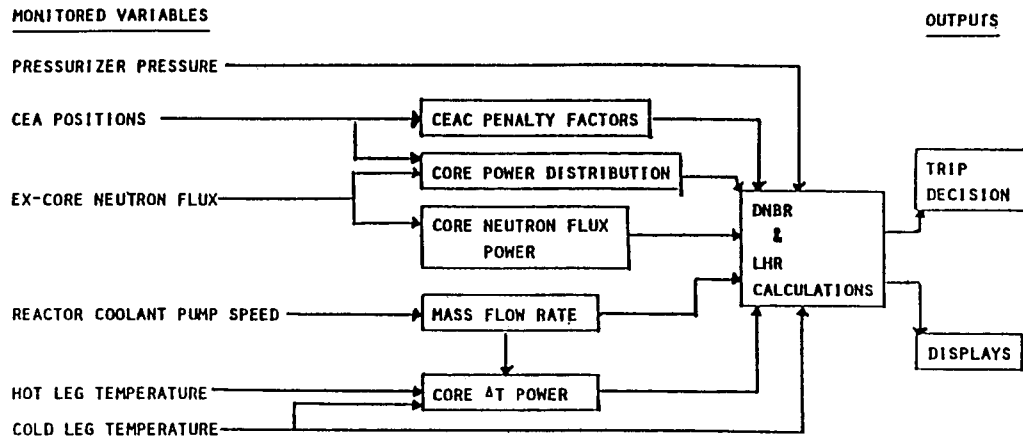


Figure 1. Simplified CPCS Block Diagram

tors based on 95/95 probability/confidence tolerance limit.

The FLAIR program is used to simulate the startup test measurements that would be used at the plant to determine certain CPC addressable constants. These constants are used in the overall uncertainty analysis to "tune" the CPC to the simulated plant (FLAIR). It is the same manner that the on-line CPC is "tuned" to the actual core.

The uncertainty analysis is performed by comparing the three-dimensional peaking factor (F_q) and DNB-OPM (DNB-Over Power Margin) obtained from the FLAIR and CETOP-D codes to those calculated by the CPC. The reactor core simulator (FLAIR) generates the three-dimensional core power distributions. Twelve hundred (1200) cases of power distributions at each of 3 or 4 burnups are used in the determination of the overall uncertainty factors for the F_q and DNB-OPM. These cases are chosen to encompass steady state and quasi-steady state plant operating conditions throughout the cycle life time.

CETOP-D determines the values of DNB-OPM which are used as the standard for the CPC simulation.

Power distributions are generated by changing power levels (20-100%), CEA configurations (first two lead banks full in to full out, PSR (Part Strength Rod) fully inserted to fully out), xenon and iodine concentration (equilibrium, load maneuver, oscillation). The power

measurement errors used for the LPD and DNBR calculations are obtained from the CPC core power synthesis error, the secondary calorimetric power measurement error, the CPC power calibration allowance to the secondary calorimetric power, and a thermal power transient offset. Detailed description of the above method can be found in Reference 10.

F_q and DNB-OPM modeling uncertainties are statistically combined with other uncertainties in calculating CPC overall uncertainty factors for LPD and DNBR calculations.

After USNRC approval of the original SCU (Statistical Combination of Uncertainties) methodology described in reference 10, CE improved its standard SCU methods for Waterford Unit beginning with Cycle 2 (Reference 11). Instead of using a reactor core simulator with a simplified, fast running DNB algorithm and built-in CPCS simulators (as described in Reference 10), an individual CPCS/SCU simulator was developed to be used with the stand alone neutronics and design thermal hydraulics design codes.

As a result, correction factors among thermal-hydraulics models are no longer needed. In addition, the CPCS/SCU simulator explicitly models startup test acceptance criteria so that separate penalty factors are no longer needed. Finally, additional uncertainty factors which were previously applied by hand following the calculation of modeling uncertainties (e.g., radial

Table 1. Uncertainty Components in SCU

A. Combined Statistically in Minimum DNBR Limit	
1.	Inlet flow distribution uncertainties
2.	Enthalpy rise factor
3.	Systematic pitch uncertainties
4.	Systematic clad O.D. uncertainties
5.	Heat flux factor
6.	CE-1 CHF correlation uncertainties (including NRC imposed cross-validation uncertainty)
7.	TORC code uncertainty
8.	Fuel rod bow penalty on DNBR*
9.	HID-1 grid penalty*
B. Modeled Explicitly in CPCS/SCU Simulators	
1.	CEA position measurement uncertainty
2.	Ex-core detector measurement uncertainty
3.	Core inlet temperature measurement uncertainty
4.	Primary coolant pressure measurement uncertainty
5.	Primary coolant flow rate measurement uncertainty
6.	Power distribution algorithm modeling uncertainties
7.	Thermal-hydraulic algorithm modeling uncertainties
8.	Rod shadowing factor measurement uncertainty
9.	Shape annealing matrix measurement uncertainty
10.	Boundary point power correlation coefficient measurement uncertainty
C. Applied Statistically to Overall Uncertainty Factors in CPCS/SCU Simulators	
1.	Radial peaking factor measurement uncertainty
2.	Fuel and poison rod bow penalty on radial peaking factors
3.	Computer processing uncertainties
4.	Reactor core simulator modeling error
5.	LPD engineering factor
D. Applied Deterministically to Overall Uncertainty Factors in CPCS/SCU Simulators	
1.	LPD axial densification factor
2.	Transient offsets on power, pressure and/or temperature as required by transient analyses
3.	CPC power calibration allowance

* applied deterministically

peaking factor measurement, fuel and poison rod bow, computer processing) are now direct input to the CPCS/SCU simulator and automatically applied to the determination of the final overall uncertainty factors. The simulator calculates the final overall DNBR and LPD uncertainty factors along with power measurement and ASI (Axial Shape Index) uncertainties. Figure 2 shows the simulator flow paths. Table 1 lists uncertainty components to be considered in the analysis which are grouped according to application method.

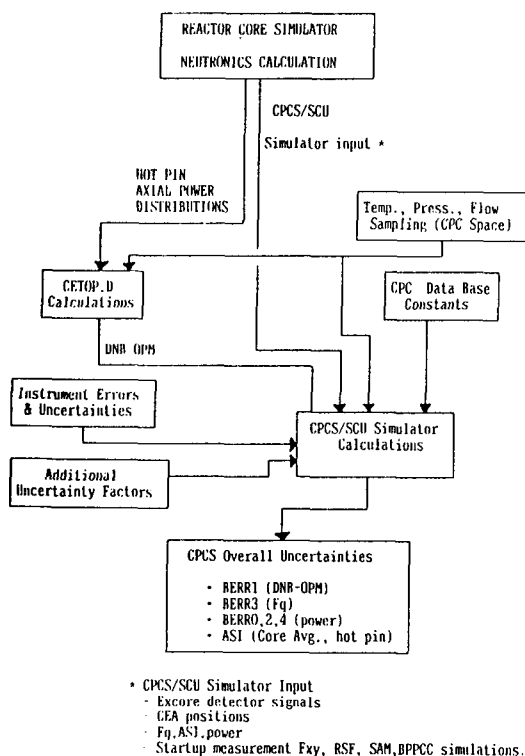


Figure 2. CPC Uncertainty Analysis for SCU

3. Setpoint Calculation

The Yonggwang Nuclear Units 3 and 4 (YGN 3&4) Cycle 1 CPCS constants are developed based on the implementation of References 6 and 7. These constants are divided into three categories, namely Addressable constants, Reload Data Block (RDB)

constants [9], and Data Base constants [8]. Addressable constants are those CPCS constants which are expected to change during the course of a fuel cycle. Their values may be changed by plant personnel via the CPCS Operator's Module. The CPCS Addressable constants are largely determined by the CPC uncertainty analysis. RDB constants are those CPCS constants which can be modified in the field using a RDB disk. The RDB constants are defined by the RDB constant analysis. The remaining CPCS constants are called CPC Data Base constants. They are determined by the CPC Data Base analysis. Figure 3 shows a simplified procedure for the CPCS setpoint calculation. Since it takes a lot of efforts to complete a setpoint calculating for the CPCS, it is decided that the preliminary design results for YGN 3 and 4 are used for the CPCS. It should be noted that the CPCS setpoints are preliminary, that is, they may be somewhat unrealistic to describe the real behavior of YGN 3 and 4.

The Westinghouse methodology [1] [4] [5], as it is understood by the authors, was used for the YGN 3&4

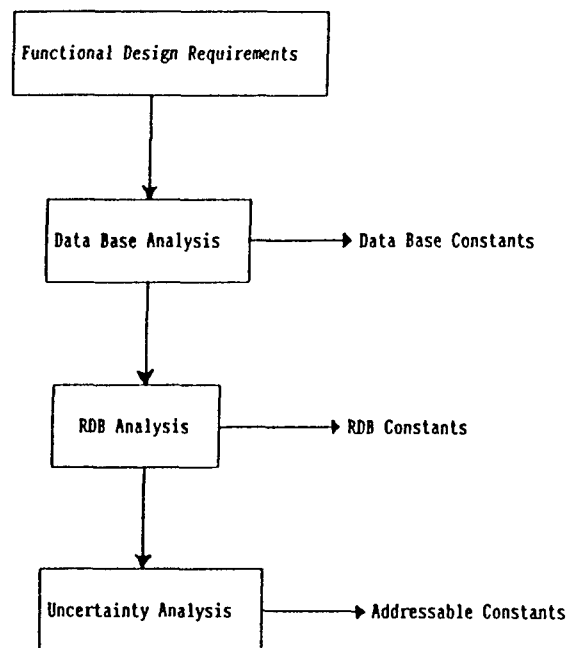


Figure 3. Simplified Procedure for CPCS Setpoint Calculation

setpoint calculation of the analog system (i.e., OP Δ T and OT Δ T systems). The following principles were applied for the setpoint calculation of the two systems (i.e., analog and digital systems):

- When a common input is needed for the two systems, the same hardware characteristic was used (example: cold leg temperature measurement).
- When an input is needed for a system only, the hardware characteristic for the input is used for that system only (example: pump speed measurement for the CPCS).

Only steady-state margin was calculated in this work, which means that:

- K_1 , K_2 , K_3 , K_4 and K_6 and to be calculated for equations (1) and (2)
- Dynamic offset effects are not considered in the CPCS.
- No arbitrary margin is included in OP Δ T and OT Δ T systems (Westinghouse methodology [4] [5] usually includes 8 to 15% additional margin in these systems).

The CPCS dynamic offsets are obtained by transient analysis which should bound the safety analysis. By considering only steady-state margin, it is possible to eliminate the margin difference effects by different safe-

ty analysis methods.

The limit DNBR value has to be calculated again from the Westinghouse methods [1] [4] [5] within the CPCS design parameter range. The CE-1 Correlation was used for this purpose since the CPCS uses it. The limit DNBR and the setpoints were calculated using the CETOP-D code. The two major components are considered in the calculation of the minimum DNBR: correlation limit DNBR and system limit DNBR.

Limit DNBR Calculation for Analog System

For the CE-1 correlation, the actual correlation limit DNBR is 1.19. To determine the system limit DNBR, the system moment method is applied to calculate the DNBR uncertainty due to the design system parameters:

$$\delta_{\text{DNBR}}^2 = \sum_i S_i^2 (\delta_i/\mu_i)^2 \quad (3)$$

where

$$S_i = \frac{1/\ln(\text{DNBR}/\text{DNBR}_{\text{nom}})}{1/\ln(X_i/X_{i, \text{nom}})}$$

X_i = design system parameters

μ_i , δ_i = mean and standard deviation of X_i

S_i = DNBR sensitivity of X_i

δ_{DNBR} = standard deviation of DNBR uncertainty

The sensitivity parameters and their uncertainty data are given in Table 2. In the sensitivity calculation, the operating ranges of key parameter are:

Table 2. Parameters for DNBR Sensitivities and their Uncertainties

Parameters	Nominal Value	δ_i
1. Primary Coolant Flow Rate	1.0	0.025
2. Core Power	1.0	0.01
3. Core Inlet Temperature [deg-F]	564.5	1.5
4. Primary System Pressure [psia]	2250	30
5. Nuclear Enthalpy Rise Hot Channel Factor (*)	1.55	0.0243
6. Engineering Enthalpy Rise Hot Channel Factor	1.0	0.015
7. Engineering Heat Flux Hot Channel Factor	1.0	0.015
8. T/H code	—	0.025

* Parameter 5 is taken from Reference [5], all the other Parameters are from the YGN 3&4 design data.

Table 3. Sensitivity Factors for the Design Parameters

Parameters	S_i^*	(δ_i/μ_i)
1. Primary Coolant Flow Rate	1.3937	0.0250
2. Core Power	-1.8789	0.0100
3. Core Inlet Temperature	-8.1070	0.0027
4. Primary System Pressure	2.2852	0.0134
5. Nuclear Enthalpy Rise Hot Channel Factor	-1.2455	0.0157
6. Engineering Enthalpy Rise Hot Channel Factor	-0.4492	0.0150
7. Engineering Heat Flux Hot Channel Factor	-1.0021	0.0150
8. T/H code	1.0	0.0250

* Sensitivity Factors were calculated by CETOP-D code with CE-1 CHF correlation.

Pressure: 1785-2415 psia

Cold Leg Temperature: 500-595°F

Flow: 90 to 120%

The above operating ranges are also used to design the CPCS. The calculated sensitivity factors (δ_i/μ_i and S_i) are given in Table 3. The CETOP-D code is run to calculate S_i 's.

Applying equation (3) with the values of Table 3, the system limit DNBR is calculated by:

$$\text{Limit DNBR} = \frac{\text{CHF Correlation limit DNBR}}{1-K \delta_{\text{DNBR}}} \quad (4)$$

where K is the factor for one-sided tolerance limit with 95/95% confidence/probability of infinite sample numbers for normal distribution.

Applying the above equation

$$\text{Limit DNBR} = \frac{1.19}{1-1.645 \cdot 0.0655} = 1.34$$

Limit DNBR with penalty is

$$= 1.34 \cdot 1.018 + 0.01$$

$$= 1.38$$

where the rod bow penalty of 1.8% and HID grid penalty of 1% are applied.

Trip Setpoint Calculation for Analog System

The OP Δ T and OT Δ T systems are designed to assure that the analog plant will not violate the LPD

and DNBR SAFDL's during an A00. The DNB design basis is satisfied by limiting the operating parameters below the DNB limit line.

The following key assumptions were made in generating the DNB limit line:

— The axial power shape is 1.55 chopped cosine.
 $y = 1.55 \cos(0.98654 \pi z/L_o)$ (5)

where $\pi = 3.14$

L_o = active core length

$-L_o/2 \leq z \leq L_o/2$

— The radial peaking factor is given by:

$$Fr = Fr_{\text{design}} [1-0.3(1-P)] \quad (6)$$

where P = relative power

Fr_{design} = design radial peaking factor (1.55 for YGN 3,4 Cycle 1)

The above two assumptions are believed to be consistent with the Westinghouse method [1] [4] [5] known to the authors.

The following additional points are also made:

— The CETOP-D code itself takes care of the core bypass flow.

— The inlet flow maldistribution is deterministically considered in the CETOP-D code.

— A conservative value of TDC (thermal diffusion coefficient) is deterministically used in the CETOP-D code.

— Each item below is deterministically treated.

- Fuel rod bow penalty on DNBR
- HID-1 grid penalty
- LPD axial densification factor (This factor is applied during the OP Δ T trip setpoint calculation)

The design basis for fuel melting prevention is satisfied by limiting the core power to 118% of nominal. The operation boundary for this basis is determined by applying equation (7) to various reactor inlet temperatures:

$$H_{out} = H_{in} + 1.18 \frac{Q}{m} \quad (7)$$

where H_{in} , H_{out} , Q and m denote reactor inlet enthalpy, reactor outlet enthalpy, core nominal power and reactor coolant mass flow rate respectively. Coolant boiling in the hot leg (reactor outlet) should be prevented to ensure the reliability of core power measurement. This requirement has been satisfied by making the enthalpy of the hot leg below the saturation enthalpy at a system pressure on the boundary of an allowable core operation region.

Since the core operation is limited also by opening of a steam generator safety valve, the condition of the valve opening needs to be considered in determining the allowable core operation region which will be used as a basis for designing the analog protection system. The safety valve opens when the steam generator pressure reaches a preset value. Since the secondary side of the steam generator can be considered in first approximation to be in saturation state, the valve opening condition is expressed by equation (8):

$$Q = UA \frac{T_{in} - T_{out}}{\ln \frac{T_{in} - T_s}{T_{out} - T_s}} \quad (8)$$

where T , in, out, s, UA and Q mean, respectively, temperature, steam generator inlet, steam generator outlet, saturated state, overall heat transfer coefficient and steam generator thermal power. T_s is the saturation temperature at the preset pressure of a safety value (1242 psig). The value (306893 MBtu/hr/°F) of UA was evaluated from the energy balance in the steam

generator at the nominal condition treating the overall heat transfer coefficient as a constant value over the various operation conditions.

The preset pressure value of the safety valve for equation (8) was taken from the minimum value of the safety valve preset pressure values of YGN 3 and 4.

Since the allowable core thermal operation region was determined so that the core can be safe in view of the design bases of DNBR and fuel centerline melting prevention, all of overpower/overtemperature ΔT protection lines which satisfy the design bases, can be basically made from the allowable core thermal operation region. The trip function were generated by representing the allowable core thermal operation region boundary with combination of straight lines in a conservative way.

Using the procedures of Reference [4], the coefficients K_4 and K_6 of the OP Δ T trip function are calculated as 1.1621 and 0.00306/°F respectively. Also the coefficients K_1 , K_2 and K_3 of the OT Δ T function are determined to be 1.1647, 0.01209/°F and 0.00089/psi respectively.

The above calculation was for the condition without the trip system error. However, there must be errors taken into account in actuation of the actual trip system. The major sources of the error are measurements of thermal state variables and system fluctuations. In order for the trip system to satisfy the design requirements in real conditions, the coefficients of the trip system need to be revised with consideration of the error.

The selected trip function error bounds [5] are, respectively, 5.96% of the full-power ΔT for the overtemperature ΔT trip function and 5.48% of the full-power ΔT for the overpower ΔT trip function. The components of the total errors are shown in Table 4. To obtain the nominal setpoint with the trip system error, the following error allowance is subtracted from the maximum allowable ΔT as follows:

Maximum allowable OP ΔT at nominal conditions 116.21

Error allowance for calibration and instrument chan-

Table 4. Error Allowance for Calibration and Instrument Channel Errors

	Range (R)	Variance ($d^2 = R^2/12$)
Calibration		
1. Calorimetric (2%)	4%	1.3
2. T _{avg} ($\pm 2^\circ\text{F}$)	1.3%	0.14 (1)
	4.9%	2.01 (2)
3. Pressure (± 8 psia)	1.5%	0.19 (2)
Signal Linearity, Reproducibility, and Bistable Error	10.73%	9.6 (3)
Total Variance for OP Δ T Trip Function:		11.04 ($d = 3.33\%$)
for OT Δ T Trip Function:		13.10 ($d = 3.62\%$)
Setpoint Uncertainty for OP Δ T Trip Function =		5.48% ($1.645 \cdot d$)
for OT Δ T Trip Function =		5.96% ($1.645 \cdot d$)

(1) OP Δ T only(2) OP Δ T only

(3) Westinghouse Typical Value (Reference 5)

nel errors 5.48

Allowing for the above errors, the nominal trip setpoint becomes 110.73

The nominal overpower ΔT setpoint equation is:

$$\Delta T_{\text{setpoint}} = 1.1073, T_{\text{avg}} < 592.75^\circ\text{F}$$

$$1.1073 - 0.00306(T_{\text{avg}} - 592.75),$$

$$T_{\text{avg}} > 592.75^\circ\text{F} \quad (9)$$

Maximum allowable OT Δ T at nominal conditions 116.47

Error allowance for calibration and instrument channel errors 5.96

Allowing for the above errors, the nominal trip setpoint becomes 110.51

The nominal overtemperature ΔT setpoint equation is:

$$\Delta T_{\text{setpoint}} = 1.1051 - 0.01209(T_{\text{avg}} - 592.75) + 0.00$$

089

(P-2235.3) (10)

4. Thermal Margin Estimation

The thermal margin for the analog system can be defined as the value of $\Delta T_{\text{setpoint}}$ when equations (9) and (10) are satisfied at nominal cold leg temperature and RCS pressure. The nominal cold leg temperature and RCS pressure are 564.5°F and 2235.3 psig. The average coolant temperature can be calculated from the following equation:

$$T_{\text{avg}} = \frac{T_{\text{hot}} + T_{\text{cold}}}{2}$$

$$= \frac{\Delta T}{2} + T_{\text{cold}} \quad (11)$$

Since $\Delta T/\Delta T_{\text{nom}}$ is $\Delta T_{\text{setpoint}}$,

$$T_{\text{avg}} = \Delta T_{\text{setpoint}} \cdot \frac{\Delta T_{\text{nom}}}{2} + T_{\text{cold}} \quad (12)$$

$$\Delta T_{\text{nom}} = 56.5^\circ\text{F} \quad (13)$$

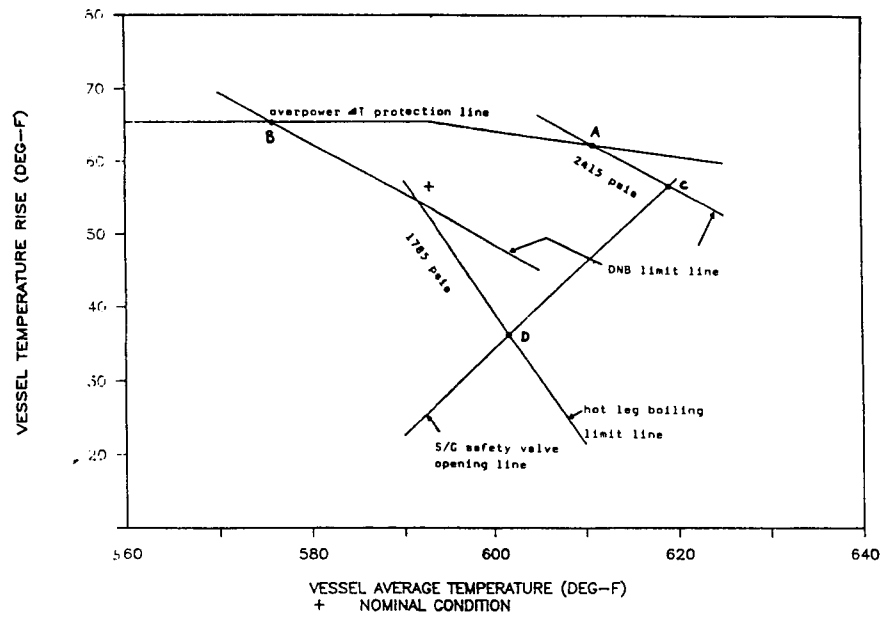


Figure 4. Intersection Points for Overtemperature Delta T System

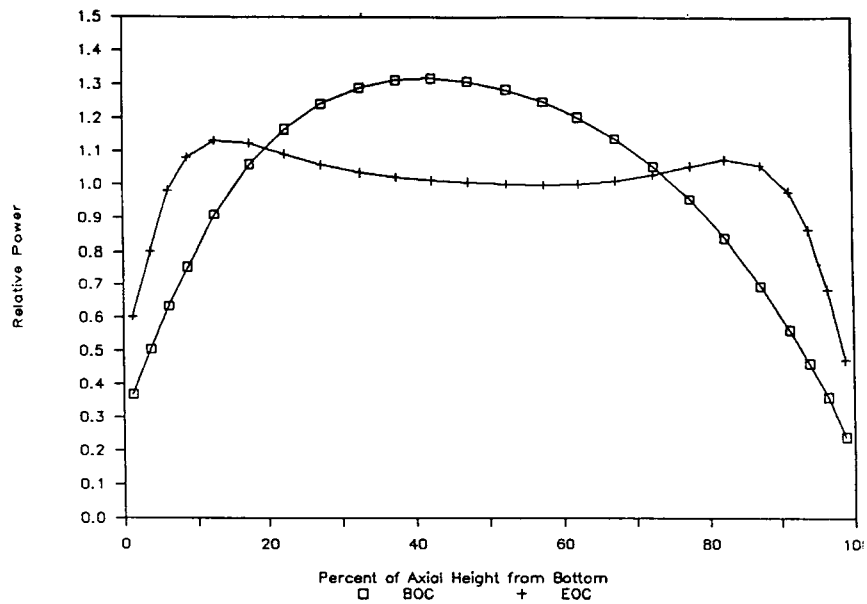


Figure 5. Axial Power Distribution of YGN 3 and 4 Preliminary Design

When equations (12) and (13) are substituted into equations (9) and (10), $\Delta T_{\text{setpoint}}$'s are 110.1% and 107.9% of the full-power ΔT for overpower and overtemperature ΔT systems respectively. This means that the steady-state margins are 110.1% for the overpower and 107.9% for the overtemperature ΔT system.

When the CPCS thermal margins are estimated at the Beginning of Cycle (BOC) and End of Cycle (EOC), the core power is increased until the DNB or fuel centerline melting trip occurs at the limiting channel. But the axial power shapes used (Figure 5) are the steady-state hot full power axial power distribution with equilibrium Xenon conditions. All other plant conditions are assumed to be in nominal conditions including cold leg temperature, RCS pressure and RCS flow rate.

For the digital protection system, the steady-state thermal margins are estimated as 142.8% and 119.0% against fuel centerline melting and DNBR respectively at BOC. Their values become 157.9% and 110.5% respectively at EOC. The EOC axial power shape of saddle type gives a smaller DNBR value resulting in smaller thermal margin at EOC than at BOC.

The steady-state margin comparison shows that the CPCS has more than 30% rated power margin compared to the OP ΔT system (specifically, 32.7% at BOC and 47.8% at EOC). However, the CPCS has almost the same margin with OT ΔT system in preventing the DNB at EOC (actually, 2.6% more than the analog system at EOC) although the digital protection system has about 10 percent more margin at BOC.

The larger margin of the CPCS against fuel centerline melting is probably due to the following reasons:

- OP ΔT system uses a fixed ceiling (118% rated power) for its setpoint (This helps gaining the OT ΔT trip setpoint).

- CPCS calculates on-line LPD value comparing it to its setpoint (21 Kw/ft).

The above advantage of the CPCS may not be important since the DNB limit is usually more limiting than the fuel centerline melting limit. Since both the

analog and digital protection systems are designed to get best but conservative margin out of the DNB limit, their net results are similar. The reason why the CPCS thermal margin is close to the OT ΔT system at EOC is probably because the CPCS has more complicated calculational procedure and many more inputs giving larger total uncertainty value. The CPCS has larger thermal margin at BOC probably because the CPCS takes advantage of the on-line plant information and the margin situation at BOC is better than at EOC due to the axial power distribution.

5. Conclusion

The distances between the operating point and the LSSS have been calculated for two typical analog and digital protection systems. The distance is called the steady-state margin. The CPCS has larger thermal margin than the analog system. The followings are the probable reasons why the CPCS has larger steady-state margins than the analog system especially in preventing the centerline melting:

- The OP ΔT system uses 118% power which is very conservative, whereas the CPCS uses the direct limiting value of 21 kw/ft

- The conservative value of 118% power helps to increase the OT ΔT trip setpoint

- The OP ΔT system has larger margin to trip than the OT ΔT system even with the 118% power

- The CPCS uses measured axial power shapes, whereas the analog protection system uses the limiting shape of "1.55 Chopped Cosine"

References

1. K.I. Han, "OP ΔT and OT ΔT Trip Setpoint Generation Methodology," Journal of the Korean Nuclear Society, Volume 16, No. 2, June, 1984.
2. R.W. Knapp and C.R. Musick, "Digital Core Monitoring and Protection Systems." International Atomic Energy Agency Meeting. Cadarache,

- France, January 26, 1977(TIS-5111).
3. M.A. Book, et. al., "Digital Protection System Upgrades," ANS 1988 Annual Meeting, San Diego, California, June 15, 1988(TIS-8346).
 4. S.L. Ellenberger, et. al., "Design Bases for the Thermal Overpower ΔT and Thermal Overtemperature ΔT Trip Functions," WCAP-8746 (Non-Proprietary), March. 1977.
 5. H. Chelemer, et. al., "Improved Thermal Design Precedure," WCAP-8567 (Non-Proprietary), July, 1975.
 6. "Functional Design Requirements for a Core Protection Calculator," CEN-305-P, Rev. 2-P, May, 1988.
 7. "Functional Design Requirements for a Control Element Assembly Calculator," CEN-304-P, Rev. 2-P, May, 1988.
 8. "YGN CPC/CEAC Data Base Document," CE-NPSD-504-P, Rev. 0-P, December, 1988.
 9. "YGN Reload Data Block Constants," CE-NPSD-508-P, Rev. 0-P, December, 1988.
 10. "Statistical Combination of Uncertainties Part II," Enclosure 1-P to LD-83-010, January, 1983.
 11. "Statistical Combination of Uncertainties for Waterford-3," CEN-343 (C)-P, October, 1985.