Journal of the Korean Nuclear Society
Volume 16, Number 1, March, 1984

《Technical Report》

Technical Review on Statistical Thermal Design of PWR Core

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(Received October 28, 1983)

가압 경수로심의 통계적 열설계에 대한 기술 검토

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(1983. 10. 28 접수)

Abstract

Studied are the statistical thermal design (STD) methods that have been developed to satisfy the design basis which protects a pressurized water reactor (PWR) core against departure from nucleate boiling (DNB) during normal operations and anticipated transients. The objective of the statistical thermal design is to quantify the thermal design margin and to remove any excess conservatism from the DNB ratio calculations through statistically combining design parameter uncertainties, while still maintaining a high level of core protection. This report describes and compares the STD methods developed by the two U.S. reactor vendors (Westinghouse and B & W). Included are the characteristics of STD, statistical treatment of uncertainties, DNB design limit development methodology and the sample application of the STD technique to core thermal design analysis. It is observed that the STD methods developed by the two vendors are similiar to each other in principle, but dfferent in the treatment of the uncertainties associated with the design parameters. The statistical thermal design is found to significantly improve the thermal design margin.

요 약

가압경수로의 정상운전상태는 물론 예상 과도상태에서도 노심내에서 DNB가 발생하지 않아야 된다는 설계근거를 만족시키는 새로운 설계방법 즉, 통계처리에 의한 열설계 방법이 개발되어 이에 대하여 검토하였다. 이같은 설계방법을 사용하여 설계변수에 대한 불확실도를 통계적으로 처리함으로써 노심설계에 따른 설계여유도를 정량적으로 계산할 수 있어 원자로심의 안전성을 충분히 유지하면서도 DNB비계산에 따른 불필요한 보수성을 배제할 수 있다. 본 기술검토보고서는 미국의 Westinghouse와 B & W원자로 제작회사가 개발한 통계적 열설계방법을 소개하고 본 설계방법의 특성을 설명하며 이어서 불확실도의 통계처리 과정, DNB설계 제한치 설정방법, 그리고 본 방법의 응용 결과를 비교하여 보여준다. 본 검토를 통하여 두 회사의 설계방법은 근본적으로 유사하나 통계처리를 위한 설계변수의 선택과 이들 불확실도의 처리방법이 다소 상이하다는 것을 알았으며 또한 본 방법의 사용으로 노심설계에 있어서 설계여유도가 현저히 증가한다는 것을 알았다.

1. Introduction

Improved methods called"statistical thermal design methods" have been developed that satisfy the design basis which protects a pressurized water reactor (PWR) core against departure from nucleate boiling (DNB) during normal operations and incidents of moderate frequency.[1),2),3)]

The overall objective of the statistical thermal design (STD) is to quantify the thermal design and to remove any excess conservatism from the DNBR calculations, while still maintaining a high level of core protection. Therefore, uncertainties associated with the DNB thermal design are statistically combined, rather than compounded, to recognize additional DNBR limits during normal operations and anticipated transient conditions.

This report describes and compares the STD methods developed by the two U.S. reactor vendors (Westinghouse and B & W; Babcock and Wilcox). Included are the characteristics of STD, statistical treatment of uncertainties, DBN design limit development methodology and sample application of the STD technique. Also observed in this report is the core thermal margin gain resulting from the use of the STD technique over the traditional thermal design method.

Values for the design parameters as inputs to the STD analyses are obtained from a typical Westinghouse 4 loop plant with 17×17 rod array fuel assemblies[4)] and a typical B & W 3, 800 Mwth plant with 205-fuel assembly core[5)], respectively.

2. Characteristics of Statistical Thermal Design

The traditional thermal design of PWR aims at maintaining core thermal protection during normal operations and anticipated transients by avoiding DNB. The minimum DNB ratio(DNBR) is calculated with the core parameters all held at conservative levels assuming worst case conditions. This minium DNBR is then compared to the DNBR limit associated with the critical heat flux(CHF) correlation being used, and these comparisons are made on the most power-limiting pin only.

The statistical thermal design still maintains the traditional criteria that the core protection should be produced through designing to avoid DNB, but changes the treatment of the uncertainties present in the DNBR calculation. It combines some of these uncertainties statistically while leaving others at conservative levels. The STD uses the DNBR calculated for the most power-limiting pin to quantify the protection afforded to the entire core. This quantification is based on best estimates with uncertainties of these estimates taken into consideration.

The calculated DNBR for a given plant condition is higher when calculated using the STD technique, since various uncertainties present in the traditional analysis are removed from this calculation. Likewise, the DNBR limit is also higher since it now incorporates those uncertainties in the DNBR limit generation. However, because these uncertainties that are linearly combined in the traditional thermal design analysis are statistically combined in the DNBR limit, the margin between the two values(calculated DNBR and DNBR limit) increases when the STD method is used.

3. Statistical Treatment of Uncertainties

To represent the variations in design parameters to DNBR variations, an uncertainty factor is defined as

$$y = \mathrm{DNBR(variable)/DNBR(nominal)} \quad (1)$$

where

DNBR(variable): DNBR based on values of the design parameters including their uncertainties and deviations from nominal values,

DNBR(nominal): DNBR based on values of all the design parameters at their nominal or best estimate values.

The DNBR uncertainty factor is considered to be affected by changes in the values of the design parameters according to a relation of the form

$$\frac{dy}{y} = S_1\frac{dx_1}{x_1} + S_2\frac{dx_2}{x_2} + \cdots S_n\frac{dx_n}{x_n} \quad (2)$$

where

x_i : value of i^{th} design parameter,

dx_i : differential change in the value of x_i,

dy : differential change in y resulting from the differential changes dx_i.

The factor S_i represents the sensitivity factor associated with the i^{th} parameter. If all the parameters are held constant except for one and the x_is are independent, the sensitivity factor is defined as

$$S_i = \frac{\partial y}{y} \Big/ \frac{\partial x_i}{x_i} = \frac{\partial(\ln y)}{\partial(\ln x_i)} \quad (3)$$

Integrating equation (2) and considering the S_i values fixed, the uncertainty factor is represented in a form

$$y = Cx_1^{S_1}x_2^{S_2}\cdots x_n^{S_n} \quad (4)$$

where C is obtained from the constant of integration.

Now, consider each of the independent design parameters x_1 as being distributed about a mean value μ_i.If y is expanded in a Taylor's series about the μ_i ignoring the higher order terms, the following expression is obtained

$$y-\mu_y = \frac{\partial y}{\partial x_1}(x_1-\mu_1) + \frac{\partial y}{\partial x_2}(x_2-\mu_2) + \cdots \frac{\partial y}{\partial x_n}(x_n-\mu_n) \quad (5)$$

The partial derivatives in equation (5) are evaluated at the point where all the x_i are at their mean values μ_i. The value of y at this point is represented by μ_y and written as

$$\mu_y = C\mu_1^{S_1}\mu_2^{S_2}\ \mu_n^{S_n} \quad (6)$$

The variance of y determined using equation (5) is given by the following expression:

$$\sigma y^2 = \left(\frac{\partial y}{\partial x_1}\right)^2 \sigma_1^2 + \left(\frac{\partial y}{\partial x_2}\right)^2 \sigma_2^2 + \cdots \left(\frac{\partial y}{\partial x_n}\right)^2 \sigma_n^2 \quad (7)$$

Using equation (4) and (6) in equation (7) leads to the equation

$$\left(\frac{\partial y}{\mu y}\right)^2 = S_1^2\left(\frac{\sigma_1}{\mu_1}\right)^2 + S_2^2\left(\frac{\sigma^2}{\mu^2}\right)^2 + \cdots S_n^2\left(\frac{\sigma_n}{\mu_n}\right)^2 \quad (8)$$

Therefore, if the sensitivity factors as well as the mean and standard deviation of the probability distribution are known for each of the design parameters, the value of σ/μ defined as the coefficient of variation for the DNBR uncertainty factor can be determined.

It is noted that equation (8) is subject to the restrictions that the x_i are independently distributed and that the variations in the x_i can be considered small. In addition the sensitivity factors S_i are considered to be constant, thus independent of the x_i.

4. Thermal Design Limit Development

4.1 Westinghouse STD Limit Development

1) Procedure

The following STD procedure has been established in Westinghouse to meet the DNB design basis:

a) determine nominal value and uncertainty of parameters at 95% confidence level.

b) determine variation in minimum DNBR associated with varitions in each parameter to establish DNBR sensitivity to each parameter on a conservative basis.

c) determine limit DNBR by utilizing the DNBR sensitivities and variances in input parameters.

2) Design Parameters and Uncertainties

Table 1. Parameters Affecting DNB Thermal Design Analysis for a Typical Westinghouse 4 Loop Plant with 17×17 Rod Array Fuel Assemblies

Parameter	Typical Values		Percent Uncertainty at 95% Probability
	Nominal	Fixed	
Primary Coolant Flow Rate, gpm	327,000	354,000	6.0
Core Bypass Flow, %	N/A	4.5	N/A
Inlet Flow to Hot Assembly, %	Variable	95	—
Core Outlet Pressure Distribution	Variable	Uniform	—
Core Power, Mwt	3411	3479	1.8
Inlet Temperature, °F	552.5	556.5	0.65
System Pressure, psia	2280	2220	1.2
$F^N_{\Delta H}$ (rod)	1.435	1.55	2.8
$F^N_{\Delta H}$ (assembly)	1.372	1.482	3.5
F^N_Z	Variable	1.55 Chopped Cosine	—
Thermal Diffusion Coefficient (TDC)	0.059	0.038	—
$F^E_{\Delta H1}$	1.0	N/A	N/A
Fuel Rod Pitch and Bowing, mils	496	N/A	N/A

An uncertainty factor can be obtained based on knowledge of the observed variation in the values of the design parameters and the limiting rod DNBR sensitivity to these parameters. The parameters considered in the DNB thermal design may be categorized into three; plant operating, nuclear and thermal, and fabrication parametetrs.

Table 1 lists the parameters affecting DNB thermal design, their typical values and percent uncertainties at 95% probability. The listed data are obtained from a typical Westinghouse 4 loop plant withl 7×17 rod array fuel assemblies. In this Table, the nominal and fixed values represent the best estimate and limiting (conservative) values of the parameters, respectively. Of the parameters in Table 1, the values for inlet flow to hot assembly, core outlet pressure distribution, F^N_Z and thermal diffusion coefficient are not included in the DNBR uncertainty factor calculation and are assigned the fixed values to add more conservatism.

The uecertainty of each parameter is obtained through one of the following schemes:

a) comparison of measured and predicted values,

b) measured error assessment, and

c) fabrication error assessment.

3) Methodology and Design Limit

In order to determine the sensitivity factors, the standard THINC-IV thermal design computer code[6] is used. A reference case is established by setting all input parameters to their nominal values. Each of the parameters considered in the DNB thermal design is then changed in value one at a time and the resulting DNBR for the peak power rod is calculated. By plotting the resulting DNBRs against the individual parameters, the sensitivities defined by equation (3) are determined.

Given in Table 2 are typical DNB uncertainty factors (coefficients of variation and sensitivity factors). Here, it is noted that the DNB behavior of fuel rods associated with each cell type is different due to the reduced flow area and additional unheated surface associated with the presence of the guide tube in the thimble cell flow channel[7]. As a result, the sensitivity factors for a typical cell differ significantly from those for a thimble cell. Due to a proprietary

Table. 2. DNB Uncertainty Factor Parameters

Parameter	Coefficient of Variation*	DNBR Sensitivity, %/% **	
		Typical Cell	Thimble Cell
$F^N_{\Delta H}$ (rod)	1.70×10^{-2}	−2.15	−1.65
$F^N_{\Delta H}$ (assembly)	2.10×10^{-2}	N/A	N/A
Vessel Coolant Flow	3.63×10^{-2}	1.39	0.79
Coolant Inlet Temperature	4.18×10^{-3}	−6.27	−4.03
Core Power	1.15×10^{-2}	−2.17	−1.69
Effective Flow Fraction	N/A	N/A	N/A
System Pressure	N/A	1.57	0.87
Fuel Rod Pitch and Bowing	N/A	N/A	N/A
F^N_Z	—	−0.77	−0.90
TDC	—	N/A	N/A

* Values for a Typical Westinghouse 4 Loop Plant with 17×17 Rod Array Fuel Assemblies
** COBRA-IV-K Calculated Values for the Korea Nuclear Unit 1

Table 3. Westinghouse DNBR Uncertainty Factor Calculation

Cell Type	Coefficient of Variation (σ/μ)	Mean (μ)	Standard Deviation (σ)	μ-1.645σ (Fu)	Limit DNBR (1.30/Fu)
Typical	0.0912	0.992	.0904	0.843	1.54
Thimble	0.0642	0.995	.0639	0.890	1.46

nature, the typical values of the sensitivity factors are not available from the Westinghouse reference. But the corresponding values for the Korea Nuclear Unit 1 calculated by the COBRA-IV-K computer program[8] are presented in the Table to help understanding the relative importance of each parameter[9].

Using the values given in Table 2 for the coefficients of varigtion and sensitivity factors, equation (8) calculates the coefficients of variation of the DNBR uncertainty factor for the typical and thimble cells. The results of the procedure used to obtain the DNBR uncertainty factors and DNBR limits for both cells are given in Table 3. From the mean and standard deviation in this Table, an uncertainty factor

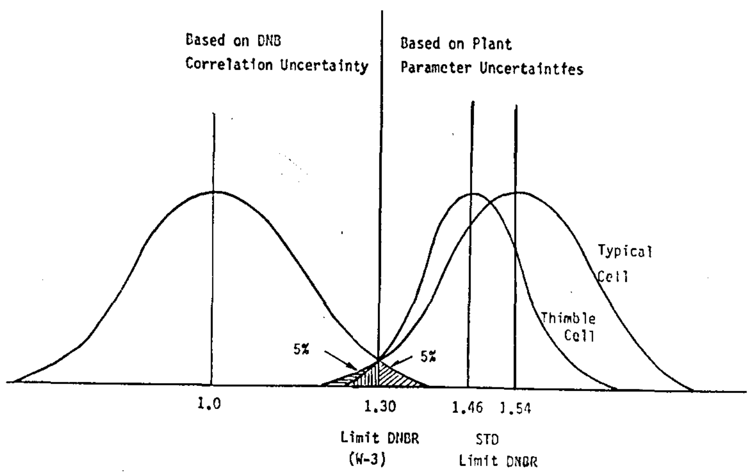


Fig. 1. Westinghouse Statistical Thermal Design Limit Development Procedure Illustration.

at the 95% probability level is obtained using the value 1.645 obtained from normal probability tables. Applying this factor to the variable DNBR of 1.30 (the ualue of DNBR limit associated with W-3 correlation), gives the values for the limit DNBR to be used at best estimate designconditions. Figure 1 illustrates how the variable and limit DNBRs are related through the normally distributed uncertainty factor for the typical and thimble cells. The limit DNBR values of this particular case are 1.54 for a typical cell and 1.46 for a thimble cell. However, it should be recognized hat these DNBR limits may vary depending on variations in plant design parameters and CHF correlations used. For example, the values of DNBR limits are 1.33 and 1.31 for typical and thimble cells for the Korea Nuclear Unit 7 &8[10] with optimized fuel assemblies in the core when using the WRB-1 correlation[11]. The DNBR limit associated with the WRB-1 correlation is 1.17.

4.2 B & W STD Limit Development

1) Procedure

The following design procedure has been established in B & W to meet the DNB design basis:

a) select the input parameters to be statistically treated and the range over which these parameters must be allowed to vary.

b) develop a formula based on thermal-hydraulic computer codes for DNBR on a pin as a function of the chosen variables. This formula, called a response surface model (RSM), will be used to generate the data for the Monte Carlo analysis that follows.

c) run a large number of paramentr combinations through the RSM and obtain the associated DNBRs. The Monte Carlo runs form the data base for determining the statistical thermal limit.

d) determine two DNBR limits that will provide the desired protection at the desired level for

(i) the maximum power limiting pin, and

(ii) the overall core protection

e) set the DNBR limit equal to the more limiting of these two values.

2) Design Parameters and Uncertainties

The parameters affecting DNB thermal design of B & W reactors are categorized into three; corewide, bundle and intrabundle parameters. The corewide parameters affect the entire core and the bundle parameters affect the thermal-hydraulic performance of the individual fuel assemblies but have negligible effects on the core average response, while the intrabundle parameters affect the thermal-hydraulic behavior within the bundle but have a negligible effect on bundlewide or corewide behavior. Listed in Table 4 are the above mentioned parameters and their nominal and extreme values available for a typical B & W 3,800 Mwth plant with 205-fuel assembly core.

The core thermal design is based on conservatively chosen values of the design variables in addition to any uncertainties associated with

Table. 4. Parameters Affecting DNB Thermal Design Analysis for a Typical B & W 3800 Mwth Plant with 205-Fuel Assembly Core

Parameter	Typical Values	
	Nomianl	Extreme
Core Power, Mwth	3800	3876
Primary Coolant Flow Rate, gpm	434,000	428,000
System Pressure, psia	2250	2205
Core Exit Pressure Dis. tribution	Variable	Uniform
Inlet Temperature, ^{0}F	568.7	570.7
Inlet Flow Distribution	Variable	0.95
$F^N_{\Delta H}$ (assembly)	1.4025	1.473
F^N_Z	Variable	1.67
Bundle Geometric Description	N/A	N/A
Active Fuel Length, inch	143	141.1
$F^N_{\Delta H}$(rod)	1.437	1.55
Intrabundle Geometry	N/A	N/A
Intrabundle Energy Exchange	N/A	N/A

them. Uncertainties are associated with manufacturing variations, control bands,measurement errors, etc. Besides the uncertainties associated with the design parameters in Table 4, B & W directly includes analytical uncertainties inherent in the tools used in the analysis such as computer code and critical heat flux correlation uncertainties.

3) Methodology and Design Limit

The overall approach to B & W STD development is to build a fast running computer model, run a large number of cases using this model, and derive the statistical limits from the results of these runs. The model developed by B & W for DNBR limit determination is referred to as response surface model (RSM) and is used to approximate the thermal codes.

The thermal-hydraulic analysis is performed on the reactor core using the LYNX1-LYNX2 computer codes.[12),13)] LYNX1 performs the steady-state thermal and hydraulic analysis of the reactor core by solving the basic conservation equations. LYNX2 calculates subchannel conditions by conserving mass, momentum and energy. The two types of subchannels are considered; the typical cell and the thimble cell. Critical heat flux ratios are calculated using the BWC correlation. Data generated with the LNYX1-LYNX2 codes and the BWC CHF correlation are used to generate an efficient RSM in the area of interest, and the uncertainty distributions for the input parameters are propagated through the RSM using Monte Carlo techniques. Validity of the RSM can be proven by comparing the actual prediction obtained with LYNX with the approximations yielded with the RSM.

The probability study is conducted with subdivision of the input variables into nonrandom and random categories. Those variables that are controlled during plant operation or included in the margin analyses in design are hele at given levels in the DNBR limit development. The parameters omitted from the margin calculation, however, are treated as random variables in the limit development. Table 5

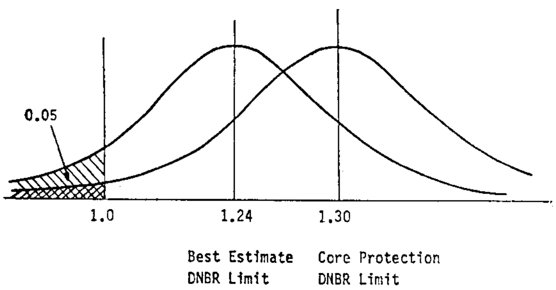
Table 5. Input Variables for Probability Study in B & W STD

Nonrandom Variables		
—Core Flow		
—Inlet Temperature		
—Core Pressure		
—Fraction of Rated Power		
—Radial Bundle Power		
—Axial Peak to Average Peaking Factor		
—Axial Peak to Average Power Location Factor		
—Local Pin Power Variation due to Positioning		
Random Variables	**Distribution**	**Type**
—Bypass Flow	Normal	RSM
—Intrabundle Area Change	Normal	Additive
—Channel Flow Area Uncertainty due to Pin Pitch and Rod Diameter	Normal	RSM
—Fuel Pin Heat Output Uncertainty due to Stack Diameter, Density and Enrichment	Normal	RSM
—Radial Power Uncertainty	Normal	RSM
—Correlation Uncertainty Based on BWC	Normal	Additive
—Code Uncertainty	Normal	Multiplicative

lists the parameters of both categories affecting DNB design and identifies the manner in which the parameters and their uncertainties are implemented in the probabilistic analysis. Those that are identified as nonrandom are used at fixed design levels, whereas the random variable levels are generated with the Monte Carlo code, SAMPLE[14]. The SAMPLE code allows the RMS to evaluate the DNBR prediction for the most power-limiting pin (MPLP). It also evaluates the sensitivity factor of each parameter.

Utilizing the sensitivities together with the distribution of the seven random variables, probabilistic analysis is performed. A number of Monte Carlo values generated for each of the seven variables are implemented and best estimate DNBR and σ(DNBR) values at 95% confidence level are obtained. The obtained value σ(DNBR) is turned out to be 0.1455 and is used to evalualuate the minimum allowable best estimate DNBR for a DNB protection of 0.95 on the MPLP. The calculated value of the best estimate DNBR is 1.24 $(1+1.645\times 0.1455)$, and the procedure is illustrated in Figure 2.

If for a given configuration of the core the LYNX code yields a best estimate of 1.24 on the MPLP, these calculations estimate that this pin will avoid DNB with an estimated probability of 0.95 at 95% confidence level. The standard deviation represents uncertainties in the seven random design variables.



* Pr $DNBR_{MPLP} \geq 1.0) = 0.95$; Power-Limiting Pin Protec ion

** Pr $(DNBR_{MPLP} \geq 1.0) = 0.976$; Core Protection

Fig. 2. B & W Statistical Thermal Design Limit Development Procedure Illustration

For corewide protection, pins other than the MPLP must also be considered. It is found that the desired corewide protection of "less than 0.1% of the pins in the core are expected to be in DNB" can be maintained, if limit DNBR on the MPLP is equal to or larger than 1.30 as shown in Figure 2. Since the corewide protection DNBR limit is more limiting than that for the MPLP, the value of 1.3 is used as the DNB thermal design criterion. In addition, to provide margin for direct offset uncertainties associated with exit pressure profile, rod bow and turbulent mixing coefficient, an additional 0.05 is added to the above mentioned statistical design limit to obtain a DNBR thermal design limit value of 1.35. This DNBR limit is used in evaluating the reactor core DNBR margin.

5. Sample Application

5.1 Application of Westinghouse STD Method

A sample illustration of how the errors in the OTΔT (Overtemperature ΔT) setpoint calcualtion using the traditional thermal design approach might be broken down is shown in Table 6 and they are compared with those for the STD approach. The traditional design technique is to substract the arithmatic sum of these errors from the maximum allowable setpoint, while in STD these errors are combined into subgroups of independent uncertainties and the subgroup errors are combined statistically. This is done by assuming that each subgroup uncertainty has a uniform probability density function between the error limits. The total uncertainty in the OTΔT setpoint at a 95% probability level is then 1.645 times the total standard deviation. From this Table, the gain in operating margin from the use of the STD

Table 6. Illustration of Westinghouse Method for Computing Nominal OTΔT Setpoint for Traditional and Statistical Approach to Core Limits

Item	Traditional Approach	Statistical Approach
Maximum Allowable Setpoint	137%	137%
Errors & Variance(σ^2)	12.8	15.6
o Calibration	5.8	6.0
1. Calorimetric	2.0	1.3
2. Tavg (±2°F), Pressure (±10 psi)	3.8	4.7
o Signal Linearity and Reproducibility	6.0	9.6
1. Process Drift	2.0	1.3
2. ΔT Trip Channel Error Tavg (±1°F), Pressure (±10 psi)	4.0	8.3
o Bistable Error	1.0	
Setpoint Uncertainty	—	6.5 (1.645σ)
Nominal Setpoint	124.2	130.5

method is found to be 6.3 percent of full power (124.2% vs 130.5% for nominal setpoint).

It is also noted from Table 6 that measurement errors in core power, inlet temperature and system pressure are also incluced in the nominal setpoint determination as well as being included in the DNBR uncertainty factor calculation. This is to insure that the effects of uncertainties in these parameters are conservatively accounted for in determining the OT ΔT setpoint.

To estimate the thermal margin during the transients resulting from the use of the STD method over the traditional thermal design method, a complete loss of coolant flow accident for a typical Westinghouse four loop 17×17 core is analyzed using both best estimate values and fixed (limiting) values for the accident parameters. Figure 3 shows DNBRs as a function of time with the traditional and statistical thermal design methods. The initial conditions for the traditional thermal design are more extreme in terms of DNB than those for the STD approach. For the traditional design case, the limit DNBR is 1.30, while it is 1.46 in a

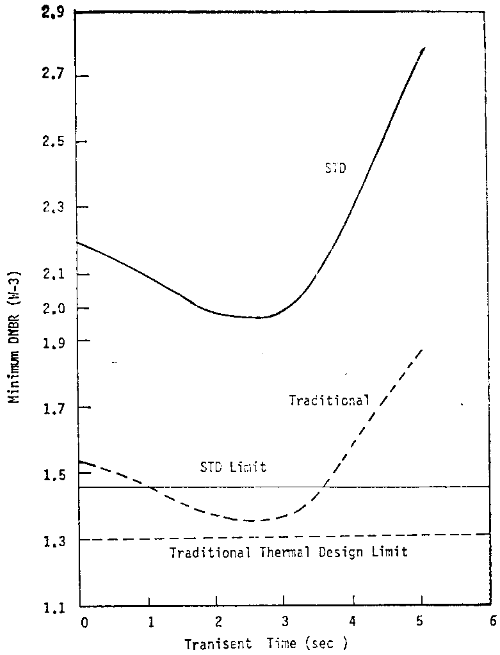


Fig. 3. Minimum DNBR Variation During Complete Loss of Coolant Flow Accident for a Typical Westinghouse 17×17 4 Loop Plant.

thimble cell for the STD case. The transients for the two cases are similar in shape, time to trip, and in the difference between the initial and the minimum DNBR. From this Figure the thermal margin gain owing to the use of the STD approach is estimated to be 0.44 in DNBR and around 22% in power margin.

5.2 Application of B & W STD Method

A typical B & W 3,800 Mwth plant conditions are used in conjunction with the BWC CHF correlation and the LYNX1/LYNX2 codes to compare the statistical and traditional thermal design methods for both steady-state and transient analyses.

The steady-state analysis comparison is based on the traditional maximum design and statistical thermal design at 112% of rated power (design overpower condition). The calculated DNBR using the statistical thermal design technique at the design overpower condition is 1.72 while that using the traditional thermal

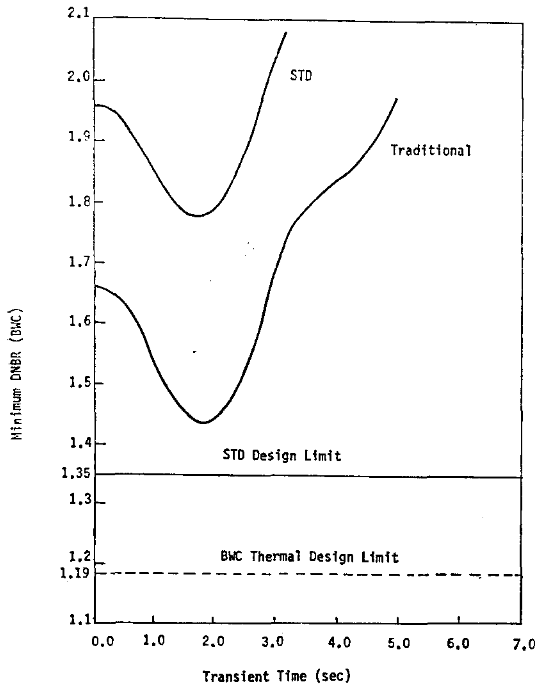


Fig. 4. Minimum DNBR vs Time for the Complete Loss of Coolant Flow Accident of a Typical B & W 3800 Mwth Plant with 205 Fuel Assembly Core.

design technique is 1.43. Considering that the thermal design limits are 1.35 and 1.19 respectively, the gain in the thermal margin resulting from the use of the STD methnd is fnund to be 0.13 that is equivalent to the power margin gain of 6.5 percent of full power.

A complete loss of coolant flow accident is selected for the transient analysis comparison. The traditional design and STD analyses are performed at 102% of rated power and the results are shown in Figure 4. Based on a DNBR margin assessment, the gain in thermal margin in this case associated with the STD methodology is 0.18 in DNBR, or approximately 9% in power margin.

6. Summary and Discussions

Based on the study results in this report, it is concluded that the STD methods developed by both vendors implement the DNB design basis and provide satisfactory DNB protection for the reactor core during normal operations and incidents of moderate frequency. It is also observed that the use of the STD method leads to a significant increase in the thermal margin through the removal of excess conservatism from the DNBR calculation while maintaining a high level of core protection.

Table7 summarizes the extent of core thermal margin gain from the use of the STD techniques for typical Westinghouse and B & W 1,200 Mwe class plants. According to this Table the Westinghouse STD method is evaluated to produce more gain in thermal margin during the transient compared to the B & W method. It is due to the difference in the treatment of uncertainties and added conservatism. For example, B & W does not include uncertainties associated with core power level, inlet coolant temperature and system pressure in the statistical uncertainty annalysis, while Westinghouse treats these parameters statistically.

When comparing the two STD methods; one by Westinghouse and the other by B &W,it is noted that the Westinghouse method is based on obtaining the design parameter uncertainties

Table 7. Summary of DNBR Gains from Statistical Thermal Design

Vendor	Case	DNBR Gain	Percent Power* Gain
W/H	OTΔT Nominal Setpoint Determination	0.126	6.3%
	Complete Loss of Coolant Flow Accident	0.44	22%
B & W	Overpower Design Condition (112% F.P.)	0.13	6.5%
	Complete Loss of Coolant Flow Accident	0.18	9%

* 2% in DNBR $\approx$ 1% power

directly from experimental results, while the B & W method obtains the values of uncertainties from the Monte Carlo analyses. It is also observed that the DNBR limit obtained through the use of B & W method is more generic compared to that of Westinghouse, that is, the latter is more plant specific.

The development of a statistical thermal design method is highly recommended, if not necessary, because it promises a gain in reactor operating margin thus relieves unnecessary burden to operators caused by severe constraints in allowed maximum power level, distribution and lower setpoint. However, it accompanies an extensive study on the selection of plant parameters, analysis of uncertainties and adequate methodelogy development.

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