Journal of the Korean Nuclear Society
Volume 16, Number 3, September, 1984

Thermal Margin Analysis of the Korea Nuclear Unit 1 Reactor Core Consisting of Standard or Optimized Fuel Assemblies

Hyun Koon Kim and Ki In Han

Korea Advanced Energy Research Institute

(Received June 21, 1984)

표준 핵연료집합체 또는 최적 핵연료집합체가 장전된 원자력 1호기 원자로심의 열적여유도 분석

김 현 균 · 한 기 인

한국에너지연구소

(1984. 6. 21 접수)

Abstract

Analyzed is the thermal margin of the Korea Nuclear Unit 1 (KNU-1) reactor core consisting of either 14×14 standard fuel assemblies (SFA) or optimized fuel assemblies (OFA). Employed for the analysis are two different thermal design methods; traditional and statistical thermal design method. Compared to the traditional design thermal method, the statistical thermal design method improves the core thermal margin utilizing best-estimate values for the core operating parameters combining their uncertainties in a statistical manner. Calculations are performed using a steady state and transient thermal-hydraulic analysis computer program, COBRA-IV-i. Calculated results show that the statistical thermal design method significantly improves the thermal margin and satisfies the core thermal design base of the KNU-1 SFA and OFA core. However, the thermal design base can not be met, if the traditional thermal design method is employed for the OFA core analysis.

요 약

표준 핵연료집합체나 최적 핵연료집합체로 구성된 원자력 1호기 원자로심의 열적여유도를 기존 열설계방법과 통계적 열설계방법을 이용하여 분석하였다. 통계적 열설계방법은 노심내 운전변수들의 불확실도를 통계적으로 처리함으로써 기존 방법에 비하여 열적여유도를 증가시킨다. 계산을 위하여 정상상태와 과도시 열수력분석 전산코드인 COBRA-IV-i를 사용하였다. 계산결과 통계적 설계방법은 열적여유도를 크게 증가시키며, 표준 핵연료집합체는 물론 최적 핵연료집합체가 장전된 원자력 1호기의 열설계기준을 만족시키는 것으로 밝혀졌다. 그러나 기존 열설계방법은 원자력 1호기 노심에 최적 핵연료집합체가 장전된 경우 열설계기준을 만족시키지 못하는 것으로 밝혀졌다.

1. Introduction

Analyzed using traditional and statistical thermal design methods is the thermal margin of the Korea Nuclear Unit 1 (KNU-1) reactor core consisting of either 14×14 standard fuel assemblies (SFA) or optimized fuel assemblies (OFA). The thermal margin, herein, may be defined as the difference between a calculated DNBR (departure from nucleate boiling ratio) and DNBR safety limit.

The traditional thermal design (TTD) method satisfies the core thermal design base that protects a core from the occurence of DNB by assuming all the operating parameters at their most extreme values. However, the statistical thermal design (STD) method utilizes best-estimate values for these parameters combining their uncertainties in a statistical manner thus recognizing additional margin to DNBR limit by removing excess conservatism involved in the TTD method.

Calculations are performed using a steady state and transient thermal-hydraulic computer program, COBRA-IV-i[1], employing the W-3 CHF correlation with modified spacer factor. Considered in the thermal margin analysis are both state and transient conditions; hot full power and design overpower conditions, and DNB limiting transients within the spectrum of the postulated accidents for the KNU-1.[2]

Thermal margin of the SFA core is calculated using both TTD and STD methods and compared to each other to recognize the advantage of one method over the other. Calculations are also performed for the OFA core thermal margin, and the results obtained using the STD method are compared with those obtained using the TTD method.

2. Development of Statistical Thermal Design Limit

Before performing the statistical thermal design it is required to develop a thermal design limit that forms a criterion on which assessment of the core safety may be based. The thermal design limit is a DNBR limit determined by combining DNBR sensitivity factors and variances of the uncertainties related to core operating parameters. [3),4),5),6),7)] Among the various core operating parameters affecting DNB, statistically treated are uncertainties related to the following five parameters; core power level, core inlect flow, inlet temperature, system pressure and nuclear enthalpy rise hot channel factor ($F^N_{\Delta H}$). Table 1 shows mean values and uncertainties along with conservatively determined sensitivity factors of the above parameters related to the operation of the KNU-1 SFA core.[8] Parameters not included in the Table are assigned the most extreme fixed values.

In the development of the thermal design

Table 1. Parameter Uncertainties and DNBR Sensitivity Facters for the KNU-1 Standard Fuel Assembly Core.

Parameter	Unit	Mean	Standard Deviation	Uncertainty Distribution	Coefficient of Variation, σ/μ	Sensitivity Factor (%/%)	
						Typicall Cell	Thimble Cell
$F^N_{\Delta H}$	—	1.435	2.44×10^{-2}	Normal	1.70×10^{-2}	−2.69	−2.16
Core Power Level	%	100	1.15	Uniform	1.15×10^{-2}	−2.82	−2.27
Inlet Temperature	°F	541.2	2.31	Uniform	4.27×10^{-3}	−7.67	−5.68
Inlet Flow	10^6lbm/ft.hr	2.40	9.07×10^{-2}	Uniform	3.78×10^{-2}	+1.47	+0.87
System Pressure	psia	2,250	17.32	Uniform	7.70×10^{-3}	+1.40	+0.85

limit of the OFA core, the statistical data in Table 1 are also used based on the assumption that the parameter uncertainty distribution of the OFA core is equivalent to that of the SFA core. DNBR sensitivity factors of the OFA core operating parameters are also assumed to be identical to those of the SFA core. Such an assumption is conservative, since a study[9] implies that the DNBR sensitivity factors of OFA core parameters are slightly lower.

Utilizing the uncertainty data and sensititity factors, the thermal design limits (DNBR limits) of both SFA and OFA core are generated for typical and thimble cells based on the W-3 correlation. Obtained values 1.52 and 1.45, respectively.

The DNBR limit used for the design overpower analysis is, however, calculated assuming that the core power level is held at 118% of rated power. The calculated DNBR limits at the design overpower condition are 1.45 and 1.41 for typical and thimble cells, respectively.

3. Thermal Margin Analysis

The KNU-1 core thermal margin is calculated using both TTD and STD methods for typical and thimble cells at steady state (hot full power and design overpower) conditions and DNB limiting transients such as control bank withdrawal accident, and partial and complete loss of the coolant flow. Listed in Table 2 are best-estimate and extreme fixed values of typical KNU-1 SFA and OFA core operating parameters affecting the thermal margin analysis.

3.1. SFA Core

A reference calculation is performed to identify the existing thermal margin of the KNU-1 SFA core based on the TTD method. Calculation results are shown in Table 3. The calculated thermal margin to the safety limit is 0.77 at hot full power condition while it is 0.25 at design overpower condition. Among the three types of accidents considered for the transient analysis, a control bank withdrawal accident terminated by OTΔT (Overtemperature ΔT) Trip at the reactivity insertion of 3 pcm/

Table 2. Comparision of Thermal-Hydraulic Design Parameters between the KNU-1 SFA and OFA Core.

Parameter	Unit	14×14 SFA		14×14 OFA	
		Nominal	Fixed	Nominal	Fixed
Fuel O.D.	inch	0.422	—	0.400	—
Pellet Diameter	//	0.3659	—	0.3444	—
Guide Tube O.D.	//	0.539	—	0.526	—
Fuel Rod Pitch	//	0.556	—	0.556	—
System Pressure	psia	2,250	2,220	2,250	2,220
Core Power Level	%	100	102	100	102
Average Heat Flux	$\frac{BTU}{hr. ft^2}$	201,200	205,230	201,940	215,160
Inlet Flow Rate	$\frac{10^6\ lbm}{hr. ft^2}$	2.40	2.29	2.20	2.10
Inlet Temperature	°F	541.2	545.2	542.7	546.7
$F^N_{\Delta H}$	—	1.435	1.55	1.435	1.55
F^N_Z	—	1.55 COSINE	1.55 COSINE	1.55 COSINE	1.55 COSINE
DNB Correlation	—	W-3	W-3	W-3	W-3

Table 3. Minimum DNBRs and Thermal Margins for Steady State and Transient Conditions of the KNU-1 SFA Core Based on Traditional Thermal Design Method

	Steady State				Transient		
	Hot Full Power		Design Overpower		Partial Loss of Flow	Complete Loss of Flow	Control Bank withdrawal
	Typical Cell	Thimble Cell	Typical Cell	Thimble Cell			
Min. DNBR	2.27	2.07	1.58	1.55	1.85	1.74	1.70
Thermal Margin	0.97	0.77	0.28	0.25	0.55	0.44	0.40

Table 4. Minimum DNBRs and Thermal Margins for Steady State and Transient Conditions of the KNU-1 SFA Core Based on Statistical Thermal Design Method

	Steady State				Transient		
	Hot Full Power		Design Overpower		Partial Loss of Flow	Complete Loss of Flow	Control Bank withdrawal
	Typical Cell	Thimble Cell	Typical Cell	Thimble Cell			
Min. DNBR	3.15	2.57	2.27	2.02	2.37	2.30	2.26
Limit DNBR	1.52	1.45	1.45	1.41	1.45	1.45	1.45
Thermal Margin	1.63	1.12	0.82	0.61	0.92	0.85	0.81

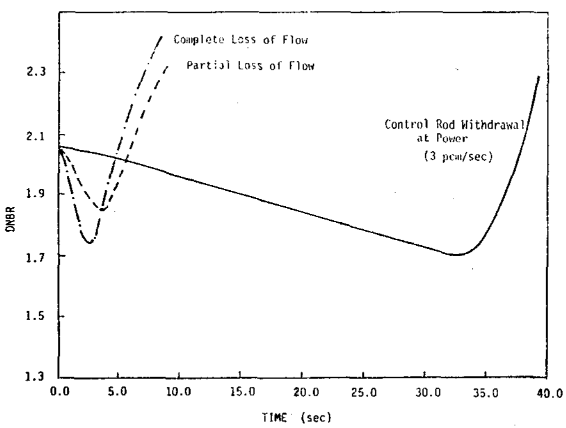

Fig. 1. Min. DNBR Versus Time during Transients for KNU-1 SFA Core

sec is found to be the most limiting transient with respect to DNB.[10] The minimum thermal margin during this transient is calculated to be be 0.40 as presented in Table 3. It is noted from the Table that the minimum thermal margin during the transient is calculated for a thimble cell only, since the thimble cell is more limiting compared to the typical cell with respect to DNB. Figure 1 illustrates changes in DNBR versus time for the three types of accidents.

Gain in thermal margin of the SFA core from the use of the STD method is investigated. Calculation results show that the thermal margin is significantly improved by the use of the STD method for both steady state and transient conditions as can be deduced from comparing the Table 3 and 4. The gain in DNBR margin is 0.35 at hot full power condition and 0.36 at design overpower condition, while it is 0.41 for the most limiting transient. Such a gain in DNBR can be utilized to improve plant flexibility thus alleviating unnecessary operating restrictions such as reactor trip setpoint improvement.

3.2 OFA Core

A major change introduced by the employment of OFA within the core from a thermal design standpoint is the reduction in fuel rod diameter (0.400 inches versus 0.422 inches in outer diameter) that leads to variations in fuel rod heat flux, temperature, DNBR and resultant thermal margin. Due to the increased fuel rod heat flux in the OFA core the thermal margin is expected to be reduced compared to the SFA core.

A reference calculation is performed to observe

Table 5. Minimum DNBRs and Thermal Margins for Steady State and Transient Conditions of the KNU-1 OFA Core Based on Traditional Thermal Design.

	Steady State				Transient		
	Hot Full Power		Design Overpower		Partial Loss of Flow	Complete Loss of Flow	Control Bank withdrawal
	Typical Cell	Thimble Cell	Typical Cell	Thimble Cell			
Min. DNBR	1.89	1.78	1.27	1.21	1.61	1.52	1.41
Thermal Margin	0.59	0.48	−0.03	−0.09	0.31	0.22	0.11

Table 6. Minimum DNBRs and Thermal Margins of the KNU-1 OFA Core for Steady State and Transient Conditions Based on Statistical Thermal Design.

	Steady State				Transient		
	Hot Full Power		Design Overpower		Partial Loss of Flow	Complete Loss of Flow	Control Bank withdrawal
	Typical Cell	Thimble Cell	Typical Cell	Thimble Cell			
Min. DNBR	2.39	2.14	1.80	1.74	2.01	1.95	1.86
DNBR Limit	1.52	1.45	1.45	1.41	1.45	1.45	1.45
Thermal Margin	0.87	0.69	0.35	0.33	0.56	0.50	0.41

if the thermal margin criterion is met when the TTD method is utilized assuming the most extreme values for the OFA core operating parameters as presented in Table 2. The calculation results are given in Table 5. It is observed from the Table that the safety criterion is met for hot full power steady state condition and transients but is violated for the design overpower condition if the TTD method is adopted for the calculation.

To recognize the thermal margin improvement in the OFA core due to the use of the STD method, the uncertainties related to the aforementioned five operating parameters are statistically combined to the best-estimate values. Table 6 summarizes the results of the steady state and transient thermal margin analysis. The calculated DNBR margin is 0.69 and 0.33 at hot full power and design overpower conditions, while the minimum margin during the control bank withdrawal accident with the reactivivity insertion rate of 2 pcm/sec is 0.41. Thus, it is noted that the STD method significantly improves the thermal margin of the OFA core and plant operating flexibility.

4. Conclusions and Recommendations

From the ressults of thermal margin analysis of the KNU-1 SFA and OFA core as summarized in Table 7 and Figure 2, it is concluded that the STD method significantly improves the thermal margin and operating flexibility compared to the TTD method. Therefore, the

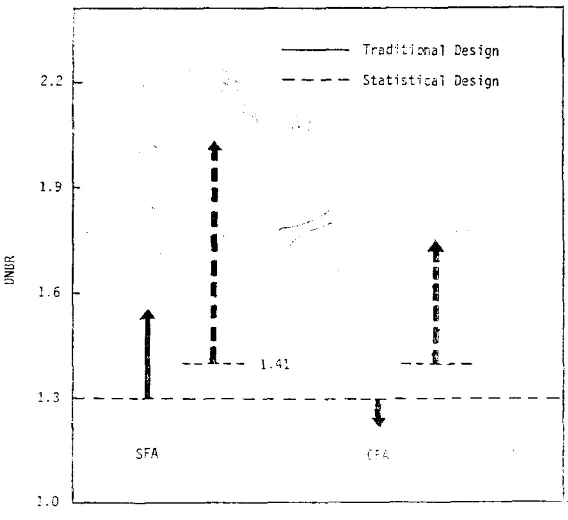

Fig. 2. Comparision of Thermal Margiu of the KNU-1 OFA Core to that of the SFA Core at Design Overpower Condition

Table 7. Summary of DNBRs and Thermal Margins of the KNU-1 SFA and OFA core Calculated Using Traditional and Statistical Thermal Design Methods.

Fuel Assembly Type		SFA				OFA			
Thermal Design Method		TTD		STD		TTD		STD	
CHF Correlation		W-3		W-3		W-3		W-3	
Fuel Cell Type		Typical	Thimble	Typical	Thimble	Typical	Thimble	Typical	Thimble
DNBR Limit		1.30	1.30	1.52 (1.45)*	1.45 (1.41)*	1.30	1.30	1.52 (1.45)*	1.45 (1.41)*
Hot FullPower	DNBR	2.27	2.07	3.15	2.57	1.89	1.78	2.39	2.14
	Margin	0.97	0.77	1.63	1.12	0.59	0.48	0.87	0.69
Design Overpower	DNBR	1.58	1.55	2.27	2.02	1.27	1.21	1.80	1.74
	Margin	0.28	0.25	0.82	0.61	−0.03	−0.09	0.35	0.33
Transient	DNBR	1.88	1.70	2.65	2.26	1.50	1.41	2.03	1.86
	Margin	0.58	0.40	1.13	0.81	0.20	0.11	0.51	0.41

SFA: Standard Fuel Assembly, OFA: Optimized Fuel Assembly
TTD: Traditional Thermal Design, STD: Statistical Thermal Design
* Design Overpower Condition

thermal design base of the OFA core is satisfied by the use of the STD method, which may not be met if the TTD method is utilized. It is also concluded that the thermal margin of the KNU-1 OFA core based on the STD method is equivalent to or slightly higher than that of the SFA core based on the TTD method. Therefore, if the KNU-1 reactor core currently loaded with SFA is going to be refuelled with OFA it is recommended that the STD method be utilized. Finally, to further improve the thermal margin it is recommended to generate more parameter uncertainty data and to use more accurate CHF correlation.

References

1. C.L. Wheeler and D.S. Rowe, et al, "COBRA-IV-i: An interim Version of COBRA for Thermal Hydraulic Analysis of Rod Bundle Nuclear Fuel Elements and Cores", BNWL-1962, March 1976.
2. "Final Safety Analysis Report for Korea Nuclear Unit 1", Korea Electric Power Company, 1976.
3. H. Chelemer, et al, "Improved Thermal Design Procedure", WCAP-7958-A, Jan. 1975.
4. K.I. Han, "Technical Review on Statistical Thermal Design of PWR Core", J. of KNS, 16 No. 1, March 1984.
5. J.A. Handschuh, "Development of a Statistical DNBR Limit", Trans. ANS, Vol. 41, 1982.
6. L.H. Boman, H. Chelemer, et al, "Thermal-Hydraulc Methods for PWR DNB Criterion Evaluations", Trans. ANS, 1981.
7. R.G. Easterling, "Some Statical Aspects of Uncertainty Analyses", Trans. ANS, June 1979.
8. H.K. Kim and K.I. Han, "DNBR Sensitivities to the Variations in PWR Operating Parameters", J. of KNS, Vol. 15, No. 4, Dec. 1983.
9. H. J. Baik and G.C. Park, "Analysis of Thermal-Hydraulic Characteristics of Optimized Fuel Assembly", Master Thesis of Seoul University, 1983.
10. K.I. Han, et al, "Reactor Kinetics and Reactivity Induced Accident Analysis", KAERI/RR-2178/80, KAERI, 1981.