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Development of In-Core Fuel Management Scoping Tools for PWR

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가압경수로의 노심내 핵연료관리용 탐색도구의 개발

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Abstract

This paper concerns with developing a simplified in-core fuel management scoping tool for PWR. For this purpose the point reactivity model is put into a fuel cycling decision code, FCYPRM. Modified Borresen's coarse-mesh diffusion theory and nodal expansion method are utilized to form a spatial neutron analysis code, CMSNAP. Numerical experiments are performed to determine a set of empirical shuffling rules for working out an automated fuel loading pattern search code, ALPS. The numerical examples are presented for verifying effectiveness and applicability of individual codes. By structuring and applying three codes for reload core design problem of a PWR, it is demonstrated that these codes provide an effective in-core fuel management scoping tool for PWR.

요 약

이 논문은 가압경수로의 노심내 핵연료 관리용 탐색코드를 개발하기 위한 것이다. 이 목적으로 점반응도모형을 사용하여 핵연료주기 결정을 위한 FCYPRM코드를 제작하였고, 수정형 Borresen의 소격확산모형과 노달전개법에 의한 중성자 공간 해석용 CMSNAP코드를 개발하였다. 또한 수치 실험을 통하여 일련의 경험칙을 수립하고 이들을 이용하여 재장전노심 핵연료집합체 배치코드로서 ALPS코드를 개발하였다. 수치계산결과를 예시함으로서 개개 코드들의 유용성과 응용성을 입증하였으며, 이들 코드들을 가압경수로의 재장전노심 설계문제를 해결하기 위한 코드로 합성, 응용함으로서 상기 코드들이 효과적인 탐색코드가 될 수 있음을 보였다.

1. Introduction

In–core fuel management of pressurized water reactors typically concerns with specifying fuel assemblies for reload core and determining fuel assembly loading scheme in safe and economic manner. This so–called reload design problem generally involves a heavy computational burden with core design codes, because a large number of fuel assembly loading patterns are to be examined in terms of reload core design criteria on power peaking, discharge burnup, cycle length etc.. Prior to detailed design computation, therefore, the scoping computation is desirable in order to evaluate, and to reduce the number of, design alternatives subjected to careful examination. The purpose of this paper is to develop simplified but effective tools for in–core fuel management scoping calculations for PWR.

As an initial attempt toward this purpose, two neutronics codes, FCYPRM and CMSNAP codes, and a loading pattern search code, ALPS, were developed. The FCYPRM code is designed to determine fuel cycling decision variables based on a point reactivity model[1]. The CMSNAP code is a spatial neutron analysis program designed to obtain the assembly–wise power and burnup distribution in the x–y geometry as well as critical soluble boron concentration. The ALPS code is an automated loading pattern search code based on the empirical shuffling rules[2]. This code is designed to generate trial fuel loading patterns, given the fuel specification of the reload core. In the following , a brief discusion on the basis, and verification, of these codes will be presented. By structuring and applying these codes for reload core design problem of KNU 2 PWR, it will be shown that these codes provides a simplified but very effective scoping tools for in–core fuel management of PWR's.

2. Description and verification of computational system

2.1. FCYPRM code

The FCYPRM is the abbreviation for the Fuel CYcling code based on Point Reactivity Model. The code is designed to determine fuel cycling decision variables such as feed enrichment, batch size, cycle length, and the like. The basis of the code is the point reactivity model represented by a lumped expression for reactivity of a mixed–assembly core, $\rho_i(B)$[1] ;

$$\rho(B_c) = \frac{\sum_{i=1}^{N} \rho_i(B_i) P_i(B_i) V_i}{\sum_{i=1}^{N} P_i(B_i) V_i}$$

The B stands for fuel burnup. The ρ_i, P_i, and V_i denote the reactivity, normaized assembly power, and the volume of the ith assembly, respectively. Due to the simplicity of the point reactivity model, the FCYPRM code provides handy solutions to a variety of fuel cycling decision problems. For instance, the FCYPRM can predict the number of fresh fuel assemblies that has to be fed into the reload core, given the cycle length, feed enrichment and the burnup distribution of the current cycle. Table 1 shows a comparison of actual fuel cycling data and prediction of the FCYPRM program for the number of fresh fuel assemblies that have been fed into the reload cores of PWR plants in Korea.

Another example of the FCYPRM application is a design of multi–cycle fueling scheme for reload cores. Table 2 shows the effect of the change of the batch size,i.e., the number of fresh fuel assemblies to be loaded on the cycle length of the KNU 2 reload cores. The N in Table 2 stands for the number of the cycle from which batch size begins to change. Needless to say, this table

Table 1. Comparision of FCYPRM Computaion and Actual Fuel Cycling Data for the Number of Fresh Fuel Assemblies that Have Been Fed Into PWRs in Korea

Korea Nuclear units	Method		Number of fresh FA's by cycle				
			cycle 2	cycle 3	cycle 4	cycle 5	cycle 6
KNU 2	actual data		40	41	40	53	53
	FCYPRM	$P_i=1$	42	41	41	53	52
		$P_i \neq 1$[a]	40	39	40	53	49
KNU 5	actual data		56	52	·	·	·
	FCYPRM	$P_i=1$	59	60	·	·	·
		$P_i \neq 1$[a]	56	62	·	·	·
KNU 6	actual data		52	57	53	·	·
	FCYPRM	$P_i=1$	52	59	58	·	·
		$P_i \neq 1$[a]	52	59	54	·	·
KNU 7	actual data		52	52	·	·	·
	FCYPRM	$P_i=1$	58	57	·	·	·
		$P_i \neq 1$[a]	52	52	·	·	·
KNU 8	actual data		53	44	·	·	·
	FCYPRM	$P_i=1$	54	49	·	·	·
		$P_i \neq 1$[a]	50	43	·	·	·

a) use P_i from nuclear design computations

Table 2. The Effect of Batch Size on the Cycle Length of KNU2

(burnup unit : MWD/kg)

cycle No.	Batch size / Burnup	40	44	48	52	56	60
N+1	cycle burnup	11.00	11.88	12.73	13.61	14.49	15.27
	discharge burnup	32.95	32.58	32.24	31.86	31.48	30.98
N+2	cycle burnup	11.76	12.77	13.67	14.49	15.27	16.04
	discharge burnup	34.87	34.37	33.77	33.29	32.83	32.30
N+3	cycle burnup	12.50	12.70	13.09	13.71	14.57	15.63
	discharge burnup	37.90	35.22	33.29	32.10	31.52	31.46
N+4	cycle burnup	11.76	12.52	13.24	14.02	14.88	15.80
	discharge burnup	35.48	34.38	33.39	32.65	32.17	31.91
N+3	cycle burnup	11.99	12.66	13.26	13.95	14.77	15.72
	discharge burnup	36.29	34.79	33.45	32.47	31.91	31.49

serves the basis of the design for the change of cycle length, which has been 12 months with the batch size of 40.

2.2. The CMSNAP code

Since the FCYPRM code is based on point

reactivity model,its applicability as a scoping tool is limited. In a word, it is inapplicable to problems where analysis for critical soluble boron, assembly-wise burnup and power distribution is called for. The CMSNAP code, a Coarse-Mesh Spacial Neutron Analysis Program, is designed to supplement this deficiency of the FCYPRM. The code CMSNAP makes use of two types of coarse-mesh methods ; a modified Borresen's 1.5 group diffusion theory method[3] and a nodal expansion method4). The user can select one or the other method, depending on his (or her) need. The computational methods are discussed in detail in ref. 3 and 4. For the purpose of comparing two methods, Fig. 1 shows the CMSNAP results for 2-dimensional IAEA benchmark problem. The modified Borresen's method is faster in computing speed than the nodal expansion method, yet the former is less accurate than the latter. In this connection, it is noted that the modified Boprresen's method takes 2.1 seconds in IBM 386 personal computer to compute the assembly power distribution, which has a core average relative error of 1.31% with regard to the PDQ reference result. On the other hand, the nodal expansion method takes 12.5 seconds on the same personal computer with a core average error of 0.89% in the assembly power distribution.

2.3. The ALPS Code

The ALPS code, an Automated trial Loading Pattern Search program, is designed to generate the trial loading patterns once the fuel assembly specification of the reload core is given. The basis of the ALPS code is the empirical shuffling rules aimed for low-leakage loading pattern. The shuffling rules consist of forbidden rules that forbid to arrange fuel assemblies into the position that may cause unacceptably high power peaking and preferred rules that prefer arranging fuel assemblies that may cause low-leakage from the core periphery. Since the rules are empirical, they may be derived by means of numerical experiments and historical reload core design data, if available.

Table 3 lists the shuffling rules that are derived via numerical experiments and incorporated into the ALPS code for the low-leakage reload core of KNU 2 PWR. Fig. 2 shows the octant core of KNU 2 which contains 21 fuel assemblies. Location of each fuel assembly is designated by two digit number in which the first and second digit denotes the row and column index respectively. With reference to Fig. 2, most of the rules in Table 3 are self-explanatory. The rules 1 and 2 are designed to avoid unaccepatably higher power peaking that may arise from loading the fresh fuels either central

7447 .7473 .7494	1.3042 1.2977 1.4708	1.4491 1.4022 1.4708	1.2065 1.2031 1.2191	.6102 .6272 .5883	.9329 .9334 .9369	.9327 .9334 .9313	.7520 .7631 .7484
	1.4301 1.4269 1.4313	1.4755 1.4468 1.4728	1.3114 1.3111 1.3113	1.0670 1.0727 1.0763	1.0349 1.0528 1.0318	.9496 .9580 .9383	.7340 .7483 .7251
		1.4657 1.4365 1.4499	1.3425 1.3212 1.3382	1.1780 1.1528 1.1936	1.0709 1.0694 1.0680	.9667 .9878 .9696	.6957 .7039 .6873
			1.1912 1.1921 1.1914	.9664 .9722 .9778	.9087 .9248 .9087	.8533 .8520 .8498	
				.4729 .4902 .4597	.6892 .7060 .7046	.6073 .5933 .6081	
					.5942 .5920 .6028		

		keff	max/avg error(x)	CPU time
a	PDQ	1.0296	-	-
b	Modified Borresen's method	1.0278	3.96/1.31	2.1 sec
c	Nodal Expansion method	1.0302	2.52/ .89	12.5 sec

Fig. 1. CMSNAP Computations for 2–D IAEA Benchmark Problem

11	21	31	41	51	61	71
	22	32	42	52	62	72
		33	43	53	63	
			44	54	64	
				55		

XY

X : column index
Y : row index

Fig. 2. Configuration of 1/8 Core of KNU 2

Table 3. Emperical Shuffling Rules in ALPS

Rule No.	Shuffling Rules
rule 1	Loading of fresh fuel into column 1,2,7 is forbidden
rule 2	Loading of fresh fuel in direct contact with another fresh fuel in column 3,4 is forbidden
rule 3	Loading of fresh fuel into the core reflector interface region where two sides face reflector is forbidden
rule 4	Loading of twice burned fuel in contact with high burnup(>20GWD/MTU) fuel is forbidden
rule 5	Load the fresh FA's into the position 54,62,63 by experiance
rule 6	Those loading patterns in which either the parameter P_1 is less than 360 or the parameter P_2 is greter than 12.5 are forbidden. where, P_1 and P_2 are defined as follows : $P_1 = 10\sqrt{\sum_{i=1}(R_i^2+C_i^2)}$ $P_2 = f_i \sum_{j=1}^{4} f_j$ where, $f_{i,j}$=normal power of i,jth node $\cong \frac{K_i}{4(K_i - C_1 k_i + k_i)} \cdot \sum_{j=1}^{4} f_j \frac{(k_j - C_2 k_j + C_2)}{k_j}$ R,C=row and columnn index of fresh fuel j=one of the 4 neighboring assembly to ith node k_i=infinite multiplication factor of ith node C_1, C_2=constants, which are dependent of fast flux
rule 7	The loading pattern, which violate the core symmetry, is forbidden

region of core or in the direct contact with another reactive fresh fuel assembly. The rules 3 and 4 are designed to avoid the loading pattern of shorter cycle length that may be caused by higher leakage of neutron from core periphery or by forming the least reactive zone in the core region. Figs. 3–6 show the results of numerical experiments which lead to the above-mentioned rules 1–5.

The rule 5 are derived from the actual fuel loading patterns of cycles 1–7 of the KNU 2. As for the rule 6, it must be noted that the parameter p1 is an indicator of how far fresh fuels are distributed away from the core center and the p2 a degree of congregation of fresh fuels in one region. Thus the rule 6 is designed to supplement rules 1 and 2 and thereby to elliminate loading pattern of higher power peak that may result from distributing fresh fuels in inner region of core and congregation of fresh fuels in one region by chance in the course of shuffling. Figs. 7 and 8

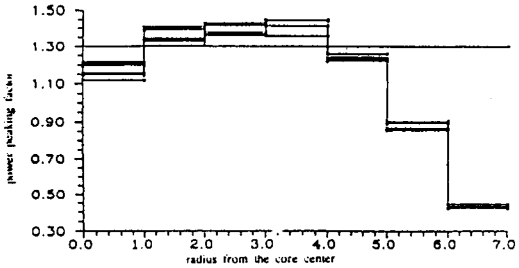

Fig. 3. Power Peaking vs Loading of Fresh Fuel in the Position of Columns 1,2

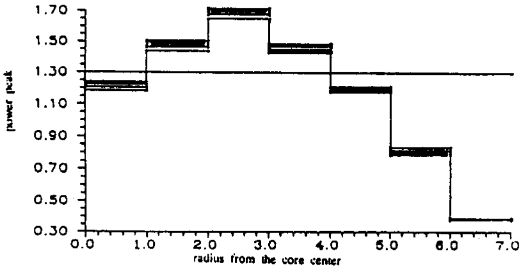

Fig. 4. Power Peaking vs Loading of Fresh Fuels in Direct Contact with Another Fresh Fuel in Columns 3,4

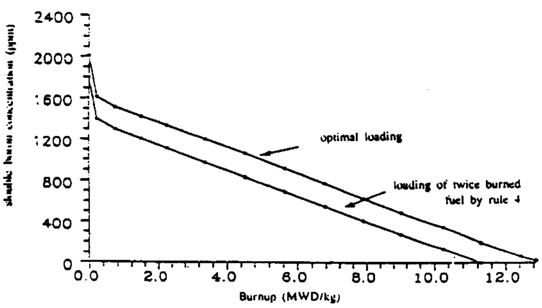

Fig. 5. Loading of Twice Burned Fuel by Rule 4

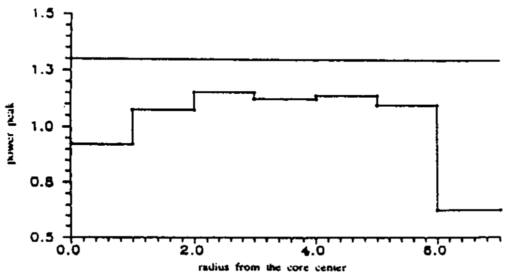

Fig. 6. Power Peaking vs Loading of Fresh Fuel in the Position 54,62,63

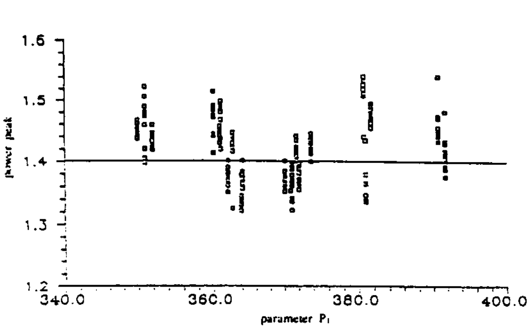

Fig. 7. Relation Between Parameter P1 and Power Peaking

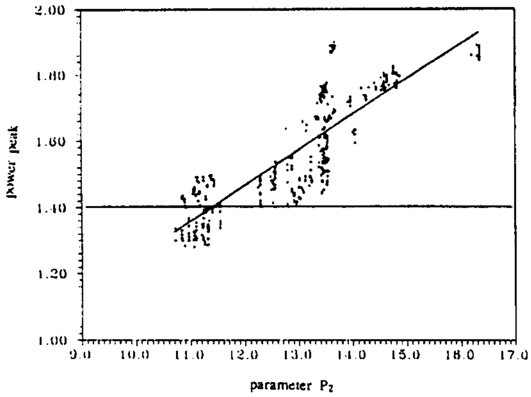

Fig. 8. Relation Between Parameter P2 and Power Peaking

TRIAL LOADING PATTERN # 1 CYCLE 6 of KNU 2

1 27.74	1 17.15	1 17.15	1 17.15	1 .00	2 .00	1 9.50
	1 17.15	1 27.02	5 .00	1 17.15	4 .00	4 13.07
		3 .00	1 17.15	1 .00	2 .00	
			1 .00	4 13.07	1 27.02	
				3 .00		

TRIAL LOADING PATTERN # 2 CYCLE 6 of KNU 2

1 27.74	1 17.15	1 17.15	1 17.15	1 .00	2 .00	1 9.50
	1 17.15	1 17.15	5 .00	1 17.15	4 .00	4 13.07
		3 .00	1 27.02	1 .00	2 .00	
			1 .00	4 13.07	1 27.02	
				3 .00		

TRIAL LOADING PATTERN # 3 CYCLE 6 of KNU 2

1 27.74	1 17.15	1 17.15	1 17.15	1 .00	2 .00	1 9.50
	1 17.15	1 17.15	5 .00	1 27.02	4 .00	4 13.07
		3 .00	1 17.15	1 .00	2 .00	
			1 .00	4 13.07	1 27.02	
				3 .00		

3 --- FA IDENTIFICATION
.00 --- BURNUP(MwD/Kg) AT BOC

Fig. 9. Illustration of a Few Trial Loading Patterns From the ALPS

show the results of numerical experiments on the correlation between the power peak and the parameters, p1 and p2.

By applying these rules to the octant core of KNU 2, the number of trial loading patterns are reduced from 21! to 214 for the sixth cycle of the KNU 2. Fig.9 illustrates the first few trial loading patterns of the 214 patterns as generated from the ALPS.

3. Application of Methods to Fuel Management Scoping Computation

The FCYPRM,CMSNAP, and ALPS codes just described are applicable either individually or in combination to a variety of fuel management problems. Since the individual applications of the codes are illustrated in the above, the integral application of the codes to the scoping computation for the reload core design of KNU 2 will be presented in the the following.

Fig. 10 shows integration of three codes into the form suitable for the scoping computations for specifying the fuel assemblies(FA) for the reload core and determining the low-leakage fuel loading pattern under the prescribed end-of-cycle(EOC) burnup condition, cycle length of reload core, feed enrichment etc.. As noted in Fig. 10, the computational procedure in this form consists of following steps ;

(1) The FCYPRM code specifies the FA's of the reload core including the number of fresh FA's, given the EOC burnup distribution of the current cycle, the cycle length of the reload core, enrichment of fresh FA, etc..
(2) The ALPS code generates and stores the trial loading patterns once the FA's for the reload core are specified at the step (1).
(3) The CMSNAP code checks whether or not each of trial loading patterns meets the specified cycle length, the peaking factor constraint, the burnup limit of the individual FA's.
(4) If either the peaking factor or the EOC burnup constraint is violated, step (3) is repeated with another trial loading pattern stored at the step (2).
(5) If the cycle length is not met with the whole of trial loading patterns from step (2), the FA specification of reload core is adjusted and the steps (2) to (5) are repeated.

Fig. 11 shows a couple of acceptable fuel loading patterns for the cycle 6 of the KNU 2 as an illustration of the final output of the scoping computation. there is no need to mention that these loading patterns will be subjected to detailed inspection with design codes for finalization of reload core design.

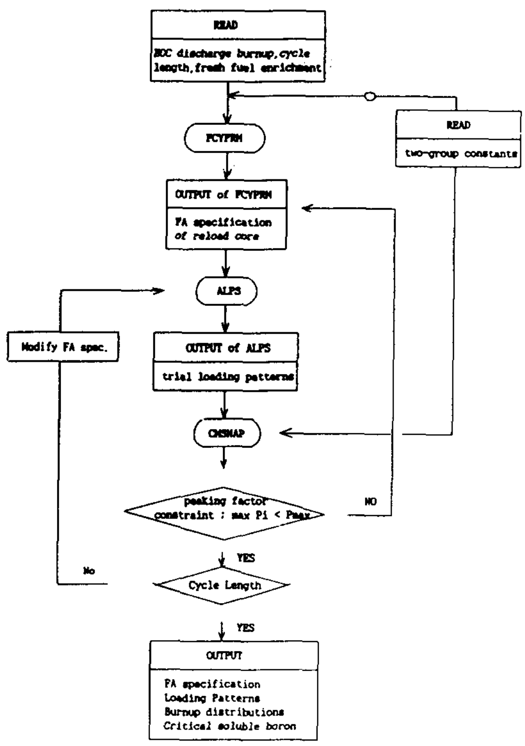

Fig. 10. Intagration of FCYPRM, ALPS, and CMSNAP Codes Into the Scoping Computation System for Reload Core Design

a) ACCEPTABLE LOADING PATTERN # 1 CYCLE 6 OF KNU 2

1 27.74 .80	1 17.15 .94	1 17.15 1.07	1 17.15 1.14	4 13.07 1.31	2 .00 1.15	1 9.50 .54
	1 17.15 1.02	3 .00 1.17	1 17.15 1.18	5 .00 1.37	1 .00 1.15	1 27.02 .36
		1 17.15 1.13	4 13.07 1.24	1 .00 1.38	4 .00 .94	
			1 17.15 1.05	2 .00 .94	1 27.02 .38	
				4 13.07 .49		

b) ACCEPTABLE LOADING PATTERN # 2 CYCLE 6 OF KNU 2

1 27.74 .83	1 17.15 .97	1 17.15 1.09	1 17.15 1.13	1 17.15 1.21	2 .00 1.21	1 9.50 .62
	1 17.15 1.04	3 .00 1.19	1 17.15 1.18	5 .00 1.38	1 .00 1.22	4 13.07 .49
		1 17.15 1.12	4 13.07 1.20	1 .00 1.36	4 .00 .95	
			1 27.02 .88	2 .00 .87	1 27.02 .37	
				1 27.02 .35	- FA ID - Burnup(MWD/kg) at BOC - Normal power at BOC	

Fig. 11. The Acceptable Fuel Loading Patterns for the Cycle 6 of KNU 2

4. Conclusion

The scoping tools presented in the above are fast runnuing in computing time and accurate enough to be compatible with the results of design computations. The computing time required to complete the scoping computation for the sixth–cycle core of KNU 2 is about 5 hours with IBM 386 personal computer. The nodal expansion method built into the CMSNAP code ensures the computational accuracy of scoping tools since the design tools such as MEDIUM2 and ROCS are based on the same nodal expansion method. Due to these properties, the scoping tools should be very useful for solving in–core fuel management problems, especially the reload core design problem of PWR's. as illustrated in this paper.

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