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A study on the core loading pattern of the VVER-1200/V491

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Abstract: The VVER-1200/V491 was a selected candidate for the Ninh Thuan I Nuclear Power Plant. However, in the Feasibility Study Safety Analysis Report (FS-SAR) of the VVER-1200/V491, the core loading pattern of this reactor was not provided. To assess the safety features of the VVER-1200/V491, finding the core loading patterns and verifying their safety characteristics are necessary. In this study, two core loading patterns of the VVER-1200/V491 were suggested. The first loading pattern was applied from the VVER-1000/V446 and the second was searched by core loading optimization program LPO-V. The calculations for power distribution, the effective multiplication factor (*k-eff)*, and fuel burn-up were then calculated by SRAC code. To verify several safety parameters of loading patterns of the VVER-1200/V491, the neutron delayed fraction (DNF), fuel and moderator temperature feedbacks (FTC and MTC) were investigated and compared with the safety standards in the VVER-1200/V491 FS-SAR or the VVER-1000/V392 ISAR.

Keywords: *VVER-1200/V491, VVER-1000/V446, loading pattern*

I. INTRODUCTION

The VVER-1200/V491 was a candidate for the Ninh Thuan I Nuclear Power Plant (NPP). Therefore, studying neutronic characteristics of the VVER-1200/V491 is required for the safety assessment of this reactor. Although the arrangements of fuel rods in fuel assemblies (FAs), the average enrichments and numbers of FAs in the 1st fuel cycle of the VVER-1200/V491 were shown in the Feasibility Study Safety Analysis Report (FS-SAR), there is still lacking of the details on the active core height and the loading pattern for the 1st cycle of the VVER-1200/V491 [1]. To do the core calculations of the VVER-1200/V491, determining its core parameters and loading pattern is necessary.

To increase reactor power, Oka showed that expanding the height of the FAs in pressurized water reactor (PWR) to about 3.7 m is possible [2]. The study of Dwiddar et al. also mentioned that the FAs height of the VVER-1200 is 20 cm higher than the VVER-1000 [3]. As shown in [3], the active height of FAs in VVER-1200 is 3730 mm while that of the VVER-1000 is 3530 mm. Besides, in order to increase the effective multiplication factor (*k-eff*) and lengthen the fuel cycle of the VVER-1000, Babazadeh et al. [4] and Karahroudi et al. [5] presented optimization methods to arrange the FAs in the core.

In this paper, to determine the loading patterns of the VVER-1200/V491, we did the following calculations: Firstly, we searched for a VVER-1000 where its FAs has the same average enrichments and fuel rods arrangements as in the VVER-1200/V491. The loading pattern of this reactor was then applied for the VVER-1200/V491 when the active core height of the VVER-1000 extended to 3730 mm. Secondly, we used the optimization program LPO-V[6] to find a core loading pattern by substituting the VVER-1200/V491 FAs. Finally, to compare two core loading patterns with safety criteria in FS-SAR, we

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used the SRAC code [7] to calculate the power distributions, delayed neutron fraction (DNF), fuel and moderator temperature coefficients (FTC and MTC) and the fuel burn-up of these loading patterns.

II. CONTENTS

A. Calculation method

The VVER-1200 fuel assemblies at 1st fuel cycle

According to the FS-SAR, at the 1st fuel cycle, the VVER-1200/V491 consists of 163 FAs which are 54 FAs with enrichment of 1.6 w/o, 67 FAs with enrichment of 2.4 w/o and 42 FAs with average enrichment of 3.62 w/o [1]. The detailed parameters of the FAs of the VVER-1200/V491 were presented in Table I.

The FA length shown in Table I was obtained from the study of Dwiddar et al. [3]. Following the study of Rahmani et al. [8], the FAs of the VVER-1000/V446 of the Iranian Bushehr NPP has the same fuel rods arrangements and FAs average enrichment as the VVER-1200/V491. The configurations of the FAs of the VVER-1200/V491 and VVER-1000/V446 were shown in Figure 1.

FA type (average enrichment)	Number	Fuel rods (enrichment)		FA pitch (cm)	FA length (cm)
		Type I	Type II		
1.6	54	311 (1.6)	-	23.6	373
2.4	67	311 (2.4)	-	23.6	373
3.62	42	247 (3.7)	66 (3.3)	23.6	373

Table I. The VVER-1200/V491 fuel assemblies in the First Loading Cycle

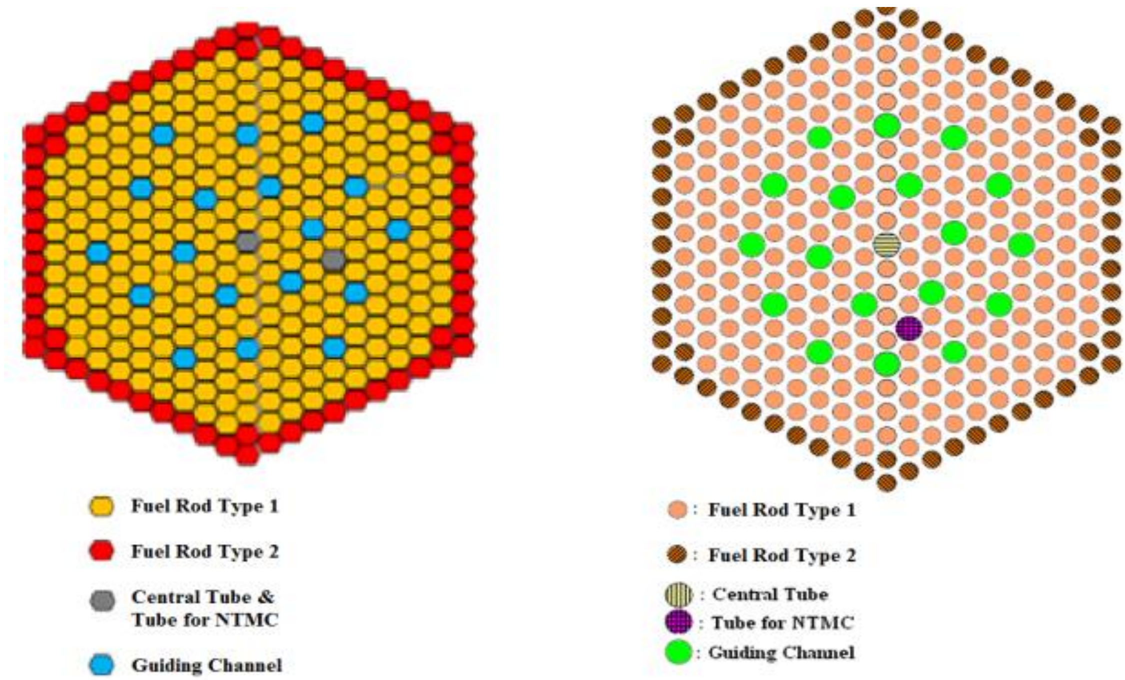

Fig 1. The VVER-1200/V491 (left) and VVER-1000/V446 fuel assemblies

Searching the loading pattern of the VVER-1200

As mentioned above, to determine the loading pattern of VVER-1200/V491, we used following methods: (1) because the VVER-1000/V446 has the same FAs types as the VVER-1200/V491, we assumed that the FAs active length was 3730 mm and then the loading pattern of the VVER-1000/V446 was applied to the VVER-1200/V491; (2) to find a loading pattern for the VVER-1200/V491, we used the optimization program LPO-V[6]. The LPO-V has been developed in Nuclear Energy Center (NEC) – Institute for Nuclear Science and Technology (INST). There are two parts of the LPO-V: (i) the neutronic calculation part in which the *k-eff* and the relative power distribution are calculated and (ii) the optimization part in which the Simulated Annealing method combined with the Tabu Search list is used to search the loading patterns at which the *k-eff* is highest and the power peaking factor satisfies the safety criteria [6]. Although the results calculated by LPO-V for the VVER-1000 were proved [6], verifying those of the VVER-1200 is needed. Thus, in this study, in addition to determining a loading pattern for the VVER-1200/V491, we also aimed to verify the applicability of the LPO-V for the VVER-1200. According to Oka [2], the Heat Flux Hot Channel Factor in PWR was limited by value of 2.32, when applying the 2-dimensional model to the core, we could calculate the core power peaking factor was 1.47. In this investigation, we assumed the limit of the PWR power peaking factor for the VVER-1200/V491 because of lacking information in the FS-SAR. The limit of the power peaking factor 1.4 was chosen in LPO-V, for conservatism.

Verifying the core loading patterns

To assess the safety features of the core in the determined loading patterns, we have to consider several characteristics of the reactor: reactor shutdown margin, reactivity insertion limit, self controllability, fuel integrity, power distribution restriction and reactor stability [2]. In this study, we focused on estimating the reactor power distributions, fuel cycle length and self controllabitity parameters as DNF, MTC and FTC.

The results were calculated by SRAC code [7]. The nuclear data library ENDF-7.0 was chosen. To evaluate the FTC, the temperature of moderator was fixed at 579K, the temperature of fuel was increased gradually from 580K to 1400K with 41 steps of 20K. For MTC calculation, the fuel temperature was fixed at 580K when moderator temperature was divided to 37 steps from 564K to 600K. The DNF, MTC and FTC were then compared with the criteria in the FS-SAR. If the standards for self controllability were not mentioned in the FS-SAR, the VVER-1000/V392 ISAR [9] was used to verify the results calculated by SRAC.

B. Results and discussions

The core loading patterns, the *k-eff* and the power distribution of the VVER-1200/V491

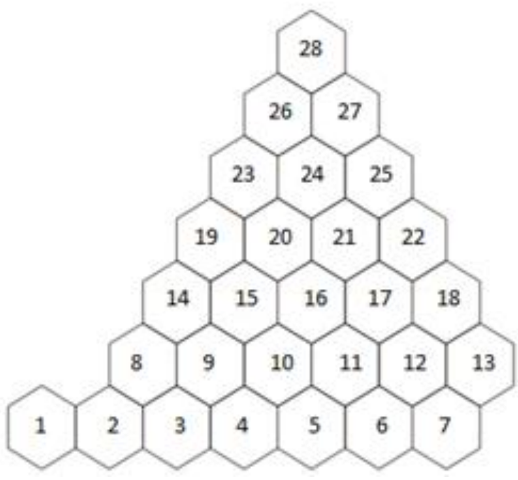

Fig. 2. The number of FAs in the 1/6 core of the VVER-1200/V491

For convenience, the positions of FAs in 1/6 core of the VVER-1200/V491 were numbered from 1 to 28 as shown in Figure 2.

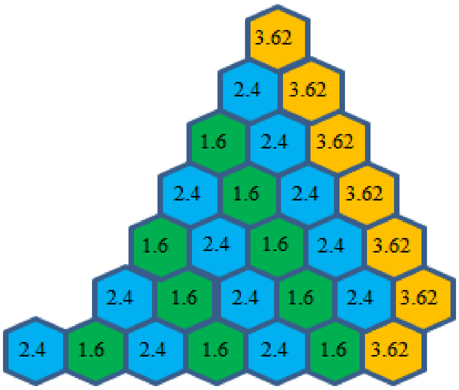

Fig. 3. The LP1 loading pattern

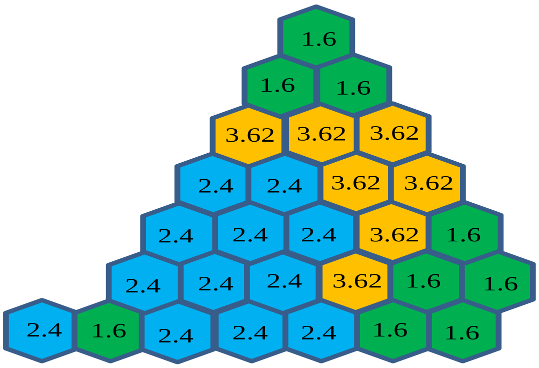

Fig..5. The LP2 loading pattern

Figures 3 and 4 presented the LP1 loading pattern when applying the VVER-1000/V446 core and the LP2 loading pattern calculated by LPO-V, respectively.

Figure 3 showed that the 3.62 FAs were arranged at the outer layer while the 2.4 FAs and 1.6 FAs were inserted alternately at the inner layers. In contrast, Figure 4 showed that in the LP2, the same average enrichment FAs concentrated together. The FAs in the LP2 were not alternately, the 2.4 FAs moved to the inner while the 1.6 FAs moved to the outer of the core.

Table II showed the *k-eff* at the Beginning of Cycle (BOC) of the VVER-1200/V491 core in 2 cases LP1 and LP2.

Configuration	*k-eff*
LP1	1.21326
LP2	1.25652

Table II. The k-eff of LP1 and LP2 at BOC

As can be seen in Figure 5, the *k-eff* in the LP2 was higher than in the LP1. In addition, the Effective Full Power Days (EFPD) of the LP2 was longer than that of the LP1. The EFPD of the LP2 was about 400 days while the EFPD of the LP1 was 350 days. Figure 6 showed the power distributions of LP1 and LP2 loading pattern at the BOC. In each hexagon, the upper number is power distribution in LP1 and the lower is that of LP2.

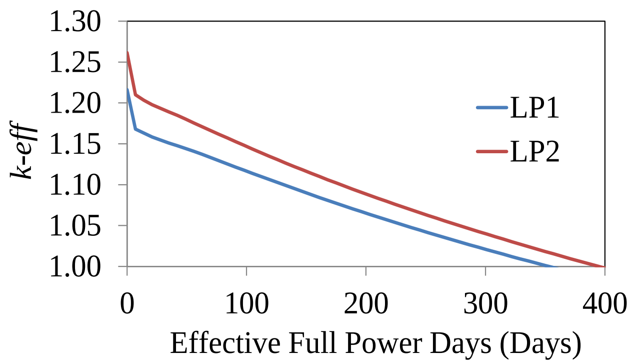

Fig. 6. The k-eff of LP1 and LP2 versus burn-up

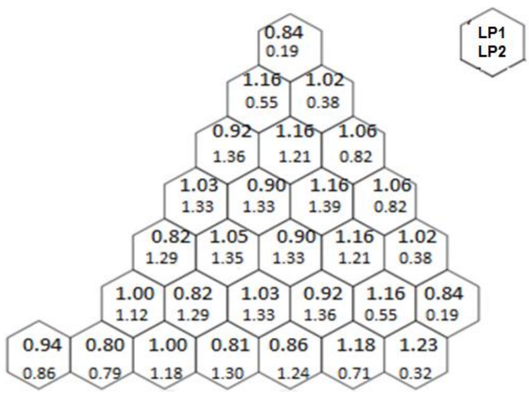

Fig. 4. Power distribution at BOC

It can be seen that 2 cases had noticeable differences of the power distributions. For the LP1, the power distribution was almost uniform, the fluctuation from 1.0 in each position was around 0.2. The power peaking factor is 1.23 at FA no.7, the lowest power distribution is 0.80 at position no.2. In case of the LP2, there were large differences between FAs positions, the outside-core FAs at positions: 7, 12, 13, 18, 26, 27, 28 had low value. High power distribution positions were found at FAs no.10, 11, 15, 16, 19, 20, 21. The power peaking factor at FA no.21 is 1.39 and the lowest power distribution is 0.19 at FAs no.13 and no.28. It was found that in the LP2, at the FAs no. 22 and 25, the power distributions were 0.82. Although the *k-eff* of the LP2 was higher than that of the LP1, it is not reasonable to choose the LP2 because of its abnormal power distribution. Additionally, when comparing to the value of power peaking factor at BOC in the FS-SAR, the peaking factor at BOC of the VVER-1200/V491 should be close to the value of 1.24 [1]. Therefore, with the power peaking factor 1.23 satisfied the operation parameter in FS-SAR, the LP1 loading pattern could be suggested as a loading pattern of the VVER-1200/V491.

To verify several self controllability parameters mentioned above, we calculated the DNF, FTC and MTC of two loading patterns. Those results were shown in the next section.

The delayed neutron fraction, fuel and moderator temperature feedbacks

Table III presented the delayed neutron fraction (DNF) calculated by SRAC in the 2 loading patterns LP1 and LP2.

Table III. The delayed neutron fraction

Group	Core DNF	
	LP1	LP2
^{87}Br	0.0002	0.0002
^{137}I	0.0011	0.0011
^{89}Br	0.0011	0.0011
^{139}I	0.0032	0.0032
^{85}As	0.0010	0.0010
^{9}Li	0.0003	0.0003
Total	0.0071	0.0070

As reported in the FS-SAR, the DNF is 0.0074 at the Beginning of Cycle (BOC) and 0.0054 at the End of Cycle (EOC) [1]. It can be seen that, at the BOC, the results of DNF of the LP1 and LP2 loading patterns were close to the DNF value in the FS-SAR.

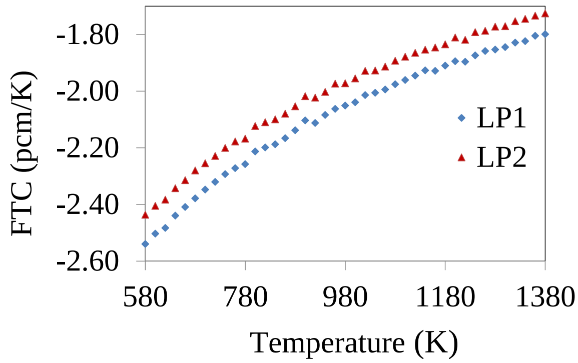

Fig. 7. The fuel temperature coefficient

Figure 7 showed the FTC in 2 configurations LP1 and LP2. When fuel temperature increased from 580K to 1400K, the reactivity feedbacks of LP1 increased steadily from -2.54 pcm/K to -1.8pcm/K, the feedbacks of LP2 were from -2.44 pcm/K to -1.73pcm/K. In the ISAR of the VVER-1000/V392, the limits for FTC vary from -3.3 pcm/K to -1.7 pcm/K at the BOC [9]. Therefore, the FTC of VVER-1200/V491 when using the LP1 and LP2 loading patterns can satisfy the criteria in the ISAR.

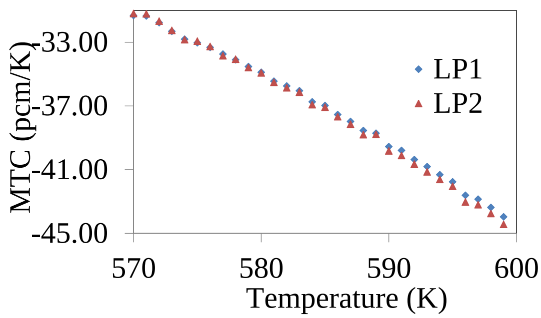

Fig. 8. The moderator temperature coefficient

Figure 8 presented the dependence of reactivity of the LP1 and LP2 loading pattern on moderator temperature. It was also seen that when increasing the moderator temperature, the reactivity curves move down from -29 pcm/K to -45pcm/K (Figure 8). The results of MTC were also compared with the criteria in the ISAR of VVER-1000/V392. As reported in the ISAR, the criteria of MTC range from -26.7 pcm/K to -54.8 pcm/K. So, the values of MTC in the LP1 and LP2 loading patterns corresponded to the criteria in the VVER-1000/V392 ISAR when those standards were absent in the VVER-1200/V491 FS-SAR[9]

III. CONCLUSIONS

In this study, 2 fuel loading patterns were suggested for the VVER-1200/V491: the LP1 – applied from the VVER-1000/V446 in the Iranian Bushehr NPP and LP2 – calculated by core optimization program LPO-V. The *k-eff* and power distribution of the 2 loading patterns were then calculated by SRAC. To verify the safety characteristics of the loading patterns, the DNF, FTC and MTC were calculated and compared with the FS-SAR of the VVER-1200/V491. In case of the safety standards absent in the FS-SAR, the DNF, FTC and MTC were compared with the criteria in the VVER-1000/V392 ISAR.

At the BOC, the *k-eff* of the LP2 was higher than that of the LP1. The core burn-up calculations also showed that the LP2 had longer burn-up than the LP1. However, the power distributions of 2 loading patterns at BOC showed that while the LP1 gave the almost uniform distribution, the LP2 showed an unusual distribution. When comparing with the parameters of the VVER-1200/V491 FS-SAR, the power peaking factor of the LP1 was close to the value in the FS-SAR. Because the information on several safety standards of the VVER-1200/V491 was absent in the FS-SAR, we used some standards of the VVER-1000/V392 ISAR to verify the self controllability parameters of the VVER-1200/V491. The results showed that the DNF of the LP1 was close to the DNF in the VVER-1200/V491 FS-SAR, the MTC and FTC of the LP1 satisfied the standards in the VVER-1000/V392 ISAR. Thus, we suggested the LP1 as a loading pattern for the VVER-1200/V491. Furthermore, loading patterns of the VVER-1000 reactors have the same FAs configurations as the VVER-1000/V446 are recommended to be applied for the VVER-1200/V491.

The power distribution of LP2 loading pattern led us to an assumption that adopting the limit of power peaking factor as 1.4 in LPO-V may affect the core power distribution. Thus, consideration for the limit of the power peaking factor in LPO-V is needed. Further improvements for the LPO-V to provide uniform power distribution in the VVER-1200 are required. Also, in future works, the loading patterns of the VVER-1000 reactors will be investigated to suggest for the VVER-1200/V491. Additionally, the neutronic – thermal hydraulic coupling calculations are required to study the safety features of the VVER-1200/V491.

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