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The Thermal-Hydraulic Effects of Thimble Plug Removal for Westinghouse type PWR Plants

B. S. JUN, E. J. PARK, K. H. KIM, B. S. PARK, K. L. JEON
Korea Nuclear Fuel Co.

ABSTRACT

The thermal-hydraulic effects of removing the RCC guide thimble plugs are evaluated for Westinghouse type PWR plants as a part of feasibility study: core outlet loss coefficient, thimble bypass flow, and best estimate flow. It is resulted that the best estimate thimble bypass flow increases about by 2% and the best estimate flow increases approximately by 1.2%. The resulting DNBR penalties can be covered within the current DNBR margin. Accident analyses are also investigated and the dropped rod transient is shown to be limiting and relatively sensitive to bypass flow variation.

I. INTRODUCTION

Thimble plugging devices are used to minimize the core bypass flow through the fuel assembly thimble tubes. Typically, all guide thimble tubes that are not under RCC locations or are not equipped with sources or burnable absorbers currently have thimble plugs inserted in them. The removal of the thimble plugs reduces the active core flow since the hydraulic resistance through the bypass region decreases, thereby increasing the bypass flow.

As it is well known, thimble plug removal offers various advantages. Firstly, it is not required to purchase a new set of thimble plugging devices because of fuel design change. Secondly, there is a time savings of approximately 8 to 12 hours each refueling. Thirdly, the potential for a time loss of few hours due to bent or damaged thimble plugs is eliminated. Fourth, ALARA considerations are improved because of reduced fuel shuffle time. Fifth, the potential for generation of loose parts due to cracked plugging device springs is reduced, and so on.

As a part of feasibility study on the thimble plug removal, the hydraulic characteristics will be investigated in terms of the core outlet loss coefficient calculation, thimble bypass flow calculation, and the change of best estimate flow for 8 Westinghouse type PWR plants. As an evaluation of thermal effect due to thimble plug removal, the DNBR margin is also examined. In addition, the effect of thimble plug removal is also evaluated in several accident conditions.

2. THE EVALUATION OF HYDRAULIC EFFECT

(1) Evaluation of Outlet Loss Coefficient for Fuel Assembly

Removal of thimble plugging devices causes a reduction in outlet loss coefficient for the fuel assembly. This outlet loss coefficient reduction for fuel assembly also causes a reduction in outlet loss coefficient for the overall core. The effect of these changes should be evaluated by the hydraulic standpoints of view. Fuel assembly outlet loss coefficient has an effect on the fuel assembly lift force, DNBR and fuel rod fretting wear, etc.

Because of the increase in bypass flow and the reduction in fuel assembly loss coefficient caused by the thimble plug removal, fuel assembly lift force decreases. Therefore, the integrity of fuel assembly hold-down spring and reactor vessel internal are conservatively maintained. In general, outlet loss coefficient mismatch due to thimble plug removal has a negligible impact on DNBR and fuel rod fretting wear.

All outlet loss coefficient values are at Reynolds number=500,000 and are based on individual assembly rod bundle flow areas. Based on the change rate of the fuel assembly outlet loss coefficient[1], the change of loss coefficients due to elimination of the thimble plugs was investigated and summarized in Table 1 before and after thimble plug removal for 8 Westinghouse type PWR. The revised top nozzle and upper core plate loss coefficients were calculated by preserving the pre-K(TN)/K(UCP) ratio.

(2) Core Bypass Flow Calculation

Core bypass flow is defined as the portion of the reactor vessel flow which is assumed to be ineffective for core heat removal. Generally, core bypass flow include outlet nozzle leakage, baffle-barrel cooling, head cooling, cavity flow, and thimble cooling. Among these bypass flow, typical core bypass flow through the thimble cooling is fractioned as much as 1.9% ~ 2.0% of total RCS flow[2]. There are two ways for the thimble bypass flow calculation in Westinghouse design methodology: one is using the BYPASS Code[3], and the other is using the generic bypass flow data[2].

The generic bypass flow calculation is based on the fact that thimble flow per tube can be generated for each core component type in the core design, adjusted for the ratio of core pressure drop between the specific and generic designs, and summed for all of the thimble locations in the core. The best estimate bypass flow using generic values is calculated assuming the following configurations:

- Each plant has an equilibrium core with one fuel type
- In order to maximize the effect of the thimble plug removal, the core with IFBA is assumed
- The fluid is incompressible, isothermal, and in a steady state

- Control rods and instrumentations are fully withdrawn and the remaining core components are fully inserted
- The fuel assembly pressure drop is the driving force for the flow through the thimbles
- The inlet temperature, the bypass flow and the best estimate flow is not changed despite of thimble plug removal for the new pressure drop calculation
- The total bypass flow is the sum of the thimble best estimate bypass flow and the reactor internal best estimate bypass flow. The reactor internal best estimate bypass flow is not changed despite of the thimble plug removal

Based on the calculated outlet loss coefficient without thimble plug, fuel assembly pressure drop was calculated using by CALOPR code[4]. With this fuel assembly pressure drops, the thimble bypass flow was calculated before and after thimble plug removal for 8 Westinghouse type PWR plants and the results were summarized in Table 2. The results of this generic evaluation was similar to those of BYPASS code evaluations[5].

(3) The change of Best Estimate Flow

The Best Estimate Flow (BEF) means the most likely maximum flow for the plant at normal operation. The BEF is calculated through the balance between pressure loss of primary loop and reactor coolant pump (RCP) head, considering the steam generator tube plugging level. From a BEF point of view, removal of thimble plug means the decrease of head loss in the core, resulting in the decrease of total head loss of primary loop. Hence, with the same RCP performance, the BEF increases with the decrease of head loss. The head loss in the primary loop is calculated from the plant geometry, that is, the length and the cross sectional area of each component.

And the performance of RCP is obtained from the homologous curve provided by manufacturer. By balancing between head loss and RCP head, the following formula is obtained:

$$\sum_{loop} \text{Pressure Loss} = \text{RCP Head}$$

The BEF is the flow at the operating point that satisfies the above condition. From the above condition, the decrease of head loss by the thimble plug removal makes the BEF increase. As an example, the BEF was estimated for the actual plant for a 3 loop PWR, Yonggwang Unit 1&2. As shown in the Figure 1, the head loss of the primary loop is composed of several elements and the head loss of the vessel including core is about 49% of the total head loss. In Table 1, the removal of thimble plug made the head loss of the core decreases approximately by 5%. Therefore, the vessel head loss decreased approximately by 3%. This decrease made the BEF increase about by 1.2% as shown in Figure 2.

As a result, the removal of thimble plug does not make any effect on the Minimum

Measured Flow (MMF) and the Thermal Design Flow(TDF), which can be maintained without change.

3. THE EVALUATION OF THERMAL EFFECT

From the standpoint of thermal design, it should be checked to assure that enough thermal margin is available to support thimble plug removal. If the thimble plug removal is performed on a current safety analysis, the DNBR margin has to be allocated to offset the penalties based on a maximum value of sensitivity of DNBR to bypass flow.

All of Westinghouse type PWR plant except KORI 2 are classified into statistical thermal design (ITDP or RTDP) plants. For statistical thermal design plants, the maximum value of sensitivity of DNBR to bypass flow[6,7] was used to set the DNB penalty due to thimble plug removal. For the deterministic thermal design plant, KORI 2, the generic DNBR sensitivity[1] to bypass flow was used. To evaluate the DNBR penalty resulted from the thimble plug removal, the increased best estimate bypass flow rate (%) of total RCS flow and maximum sensitivities were conservatively used. DNBR sensitivities, and DNBR penalties listed in Table 3.

4. ACCIDENT ANALYSES

To evaluate the effect of thimble plug removal in accident analyses, the flow reduction transient (loss of flow) and the transients involving Rod Control Cluster Assemblies(RCCA) malfunction were investigated. As a Condition IV event, locked rotor was also examined against the thimble plug removal. The DNB design basis for these accidents is satisfied if the minimum DNBR is not less than the limit DNBR.

For Ulchin plants, the total core bypass flow before and after thimble plug removal was summarized in Table 4 and accident analyses were performed using those values. The results of these accident analyses were given in terms of the DNBR change in Table 5. The analyses of these transients were performed by the THINC IV code[8] and based on Ulchin 1,2 Reload Transition Safety Report.[9]

As a result of analyses, the dropped rod transient was found to be the limiting and the most sensitive to the total core bypass flow increase. The minimum DNBR violates the safety analysis limit DNBR of Ulchin plants and the net remaining DNBR margin is allocated to cover this DNBR penalty as listed in Table 5.

4. CONCLUSIONS

From the results of core thermal-hydraulic characteristic evaluations, the thimble plug removal results in an increase of the core bypass flow (decrease of the active core flow) and an increase of the total RCS flow (BEF). The following conclusions and recommendations are obtained.

1) In support of the feasibility study on thimble plug elimination, values for top nozzle and upper core plate outlet loss coefficient, fuel assembly loss coefficient and core loss coefficient have been revised. It is resulted that the core loss coefficients decreases approximately by 5% due to the thimble plug elimination.

2) Based on the revised core component loss coefficients, the thimble bypass flow calculations are performed according to the pressure drops which is the driving force for the flow through the thimbles. It is shown that the best estimate thimble bypass flow increases approximately by 2%.

3) Due to the fuel assembly hydraulic loss coefficient reduction, the best estimate primary system flow rate is estimated that there will be a slight increase in best estimate flow (approximately 1.2%). The increased BEF is in proportion to the vessel resistance decrease.

4) Using the maximum DNBR sensitivities to bypass flow and increased the thimble bypass flow, the DNBR penalties are obtained. It is turned out that the current net DNBR margin is sufficient to cover the DNBR penalties. However, some plants lose a major portion of their DNBR margin due to thimble plug removal. An alternative idea like the introduction of the advanced thermal design methodology may be necessary for the thimble plug removal.

5) According to the accident analyses, the dropped rod transient is found to be the limiting and the most sensitive. Some accident and transient analyses are not bounded for the licensed safety analyses, but current the DNBR margin is adequate to cover the resulted penalties.

In further study, the precise BEF calculations, reactor pressure vessel system analyses, the control rod wear evaluation, the fuel rod design, core design, safety analyses and so on, will be performed for the completion of the feasibility study on the thimble plug removal.

REFERENCES

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Table 1 The change of loss coefficient before and after thimble plug for fuel type

Component Loss Coefficient	14x14 OFA (KORI 1)	14x14 OFA (w/o TP)	16x16 STD (KORI 2)	16x16 STD (w/o TP)	17x17 V5H (K3,4,Y1,2, U1,2)	17x17 V5H (w/o TP)
△PFO	-	-0.69	-	-1.0*	-	-1.0
PFO	3.61	2.92	2.80	1.80	2.80	1.80
K(Top Nozzle)	1.34	1.08	0.65	0.42	0.73	0.47
K(Upper Core Plate)	2.27	1.84	2.15	1.38	2.07	1.33
K(TN)/K(UCP)	0.590	0.590	0.302	0.302	0.353	0.353
K(FA)	17.45	17.19	15.52	15.29	17.4	17.14
C1	73.91	72.81	65.73	64.76	73.69	72.59
K(core)	22.32	21.63	18.68	17.68	20.00	19.00
C2	94.53	91.61	79.11	74.88	84.71	80.47

* 16x16 STD △PFO is not available(17x17 V5H △PFO is used).

Table 2 The change of pressure drops and best estimate thimble bypass flows

Plants	BE Thimble BP(w/ TP) (%)	$\triangle P_{FA}$ (w/ TP)	BE Thimble BP(w/o TP) (%)	$\triangle P_{FA}$ (w/o TP)	Changed BEBF rate(%)	$\triangle P_{w/\ TP} - \triangle P_{w/o\ TP}$
KORI 1	0.927	17.625	2.615	17.349	1.688	0.276
KORI 2	1.673	22.527	3.405	22.173	1.732	0.354
KORI 3	1.564	21.800	3.415	21.455	1.851	0.345
KORI 4	1.565	21.683	3.414	21.339	1.849	0.344
YONGGWANG 1	1.565	21.683	3.414	21.339	1.849	0.344
YONGGWANG 2	1.565	21.722	3.414	21.377	1.849	0.345
Ulchin 1,2	1.502	19.656	3.407	19.344	1.905	0.312

Table 3 The DNBR sensitivities and resulted DNBR penalties

Sensitivity / Plants	Maximum DNBR Sensitivities to flow	increased thimble BEBF rate(%)	DNBR Penalties
KORI 1	1.338	1.69	2.26
KORI 2	1.200	1.73	2.08
KORI 3	1.530	1.85	2.83
KORI 4	1.530	1.85	2.83
YONGGWANG 1	1.530	1.85	2.83
YONGGWANG 2	1.530	1.85	2.83
Ulchin 1,2	1.530	1.91	2.92

Table 4 The change of total core bypass flow for Ulchin Unit 1,2

	Total Core Bypass Flow (w/ TP) (%)	Total Core Bypass Flow (w/o TP) (%)
Ulchin 1,2	5.6	7.59

Table 5 The results of accident analysis by total core bypass flow change

Accident \ Min. DNBR	Min. DNBR (typ/thm) w/ TP	Min. DNBR (typ/thm) w/o TP	△DNBR(%)	DNBR Penalties
Loss of Flow	1.879/1.850	1.838/1.813	2.18	-
Static Rod Misalignment	1.764/1.712	1.721/1.674	2.44	2.1
Dropped Rod	1.769/1.711	1.724/1.670	2.54	2.3
Rod Withdrawal from Subcritical	1.736/1.716	1.708/1.691	1.61	-
Locked Rotor	1.740/1.740	1.716/1.719	1.38	1.4

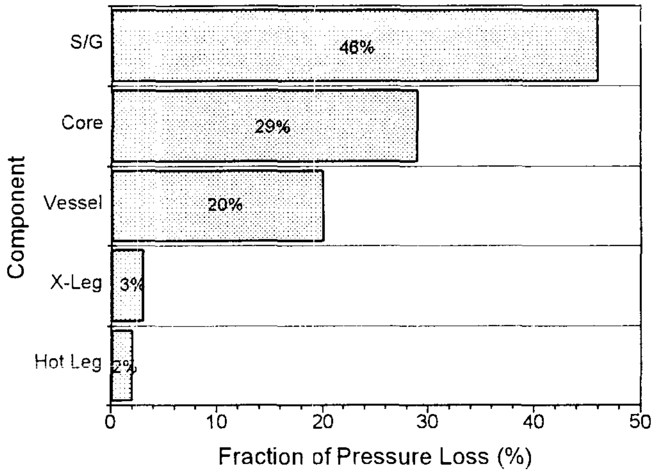

Figure 1. Pressure Loss Distribution (w/TP) for YONGGWANG Unit 1,2

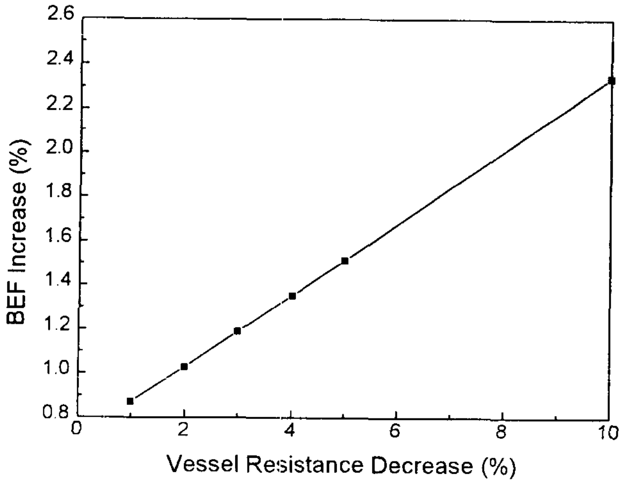

Figure 2. Relation of BEF and Vessel Resistance for YONGGWANG Unit 1,2