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Development of Permanent Reactor Cavity Pool Seal Using Optimal Design Technique

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ABSTRACT

For the development of the permanent reactor cavity pool seal assembly (PPSA), an optimization technique is applied in order to obtain the best sectional shape that could minimize the maximum stress due to design loading. The stress analysis and the fatigue analysis for the PPSA are also carried out for each plant loading condition to evaluate the structural integrity during the plant's lifetime. The stress analysis indicates that the PPSA experiences some plastic deformation, but the failure is not anticipated, because the stress is significantly lower than the minimum ultimate tensile strength of the material and the cumulative usage factor for fatigue analysis is lower than 1.0. It was found that the PPSA could be incorporated into the design of the Korean Next Generation Reactor (KNGR) as well as the Korean Standard Nuclear Plant (KSNP).

INTRODUCTION

The temporary Reactor Cavity Pool Seal Assembly (PSA) is used to seal the annulus gap between the reactor vessel flange and the refueling pool floor to allow the water level to be raised for refueling, as shown in Figure 1. Recently, by application of the Leak-Before-Break concept to reactor coolant piping the local pressurization in the reactor cavity is eliminated. Subsequently it becomes possible to permanently install the PSA, even during normal operation. This new design feature is called the Permanent Reactor Cavity Pool Seal Assembly (PPSA). By incorporating the PPSA, the critical path time of installing and removing the temporary PSA can be reduced, which results in an increase in plant availability and a decrease in radiation exposure to the refueling personnel.

In this paper the preliminary results of PPSA development for incorporation into the KNGR design are presented. An optimization technique is applied in order to obtain the best sectional shape of the PPSA for the stress reduction due to design loading. The stress analysis and the fatigue analysis of the developed PPSA are also carried out for each plant loading condition to evaluate the structural integrity during the plant's lifetime.

DESIGN REQUIREMENTS

Design Requirements for the PPSA are established in accordance with the requirements of the KNGR. The following major requirements shall be satisfied in the design of the PPSA:
(1) The PPSA is classified as non-nuclear safety and seismic category II component.

(2) Load Condition

- Level A Service Loadings : dead weight, thermal load due to temperature difference
- Level B Service Loadings : dead weight, thermal load due to temperature difference, IRWST load
- Level D Service Loadings : dead weight, thermal load due to temperature difference, SSE
- Refueling Loadings : dead weight, hydraulic pressure
- Number of cycles during lifetime :
  - Plant Heatup : 300 cycles
  - Plant Cooldown : 300 cycles
  - IRWST : 300 cycles
  - SSE : 20 cycles
  - Refueling : 60 cycles

(3) Interface Requirements :

- An access hole for maintenance shall be provided.
- A cooling air flow path shall be provided.
- The loads initiated from the PPSA and transferred to the reactor shall be minimized.
- The PPSA shall not interfere with multiple stud tensioner, integrated head assembly, refueling machine, ex-core detector and thermal neutron streaming shield block.

As the PPSA is in the refueling water environments, it shall be made of the stainless steel.

SECTIONAL SHAPE DESIGN USING OPTIMIZATION TECHNIQUE

The temporary PSA, which is subjected to only a hydraulic pressure of 26 feet of water, is of a flat plate type. However, the PPSA is subjected to the thermal expansion load of the reactor vessel in a radial direction and a SSE load. These loads induce a bending stress and a shear stress due to lateral displacement. Therefore, the PPSA has to be configured that these loads will be minimized.

Various types of cross-section shapes have been studied for the PPSA on the basis of Level D Service Loadings which are anticipated to cause maximum stress [1]. In this paper a J-type shape, which facilitates the fabrication and the installation, is chosen.

Figure 2 shows the shape and the design parameters of the PPSA with the J-type section. The PPSA consists of a seal plate, a flexible seal plate, supports, leveling bolts and access holes with covers. The seal plate is extended over the flexible seal plate to protect from the fuel assembly drop. The thickness of the seal plate (T2) is designed to be 1.5 inches. The length of the flexible seal plate (L1+R) is 12 inches, which has to be long, that is as long as possible, to absorb the shear force. The height of the flexible seal plate (L+R) is limited to less than 8.0 inches to prevent interference with the refueling machine. The above conditions are converted to formulate the optimization equation(1) as follows :

$$\begin{aligned} &\text{Find } T, R \text{ and } L \\ &\text{to minimize } \{\max \text{S.I.}\} \\ &\text{subject to } \quad 0.125 < T < 0.35 \\ &\qquad\qquad\quad 0.3 < R < 1.0 \\ &\qquad\qquad\quad 1.0 < L < 7.0 \\ &\qquad\qquad\quad L1 = 12 - R. \end{aligned} \tag{1}$$

where S.I. is stress intensity according to ASME B & PV Code [2].

The deadweight and the NOP load of Level D service loading are axisymmetric and the SSE is line symmetric. Therefore, a 3-dimensional semicircle finite element model is developed for optimal design. The 4-node flat plate (SHELL 63) element in ANSYS [3] is used, and the model has 1329 nodes and 1256 elements. All degrees of freedom of the nodes, which correspond to the points connected to the reactor vessel seal ledge and the refueling floor embedment, are restricted. The symmetric boundary conditions are applied to the nodes on the symmetric face.

The optimal design of the PPSA is carried out using the design optimization routine of ANSYS. Figure 3 shows the variation trend of the design parameters (T,R,L) and objective function (SIMX; maximum stress intensity) in the process of optimal design. This figure shows that it is converged at the eighth (8th) iteration. The maximum stress intensity decreased from 199.41 ksi in the initial design to 183.40 ksi at the eighth (8th) iteration. The optimal design parameters are shown in Table 1.

DETAIL DESIGN AND ANALYSIS

For the detailed analysis, the design values in Table 1 are used. The seal plate is extended over the flexible seal plate to protect from the fuel assembly drop, as shown in Figure 4. There are eight (8) access holes on the seal plate. Figure 5 shows the symmetric half of the PPSA for the ANSYS analysis model. The PPSA has the fundamental frequency of 51.5 Hz, and the static analysis is allowed for PPSA under the seismic loads since it can be considered as a rigid component. Figure 6 shows the nodal stress intensity distribution and the maximum stress intensity region due to Level D service loading. The maximum stress intensities for each service loading condition are calculated as shown in Table 2. The maximum equivalent stress under Level A and Level D service loadings is higher than the minimum yielding tensile strength of 30.0 ksi, which means that plastic deformation occurs. The plastic analysis is performed under Level D service loading which causes the highest stress intensity. From the fatigue analysis the maximum stress intensity under Level D service loading turns out to be 41.15 ksi, lower than the minimum ultimate tensile strength of 75.0 ksi. Therefore, no failure for the PPSA is anticipated.

During the design lifetime of 60 years, the repeated load acting on the PPSA must be analyzed to evaluate fatigue damage. Fatigue analysis is carried out in accordance with ASME Code Section III, NB-3222.4, and the cumulative usage factor is calculated to be 0.18. This value is less than 1.0, which proves that the PPSA can maintain structural integrity during the design lifetime.

CONCLUSION

To permanently seal the annulus gap between the reactor vessel seal ledge and the refueling pool embedment the Permanent Reactor Cavity Pool Seal Assembly for the KNGR is developed using an optimal design technique. The following results are obtained from this study:

(1) The PPSA is classified as non-nuclear safety and seismic category II component. The deadweight, the reactor vessel thermal expansion load, SSE, IRWST load and the hydraulic pressure shall be considered as the design loads.
(2) The J-type shape is selected from installation and fabrication points of view. The design parameters are selected to produce the minimum stress intensity using an optimal design technique.
(3) The maximum stress intensity under Level D service loading is significantly lower than the minimum ultimate tensile strength, and the cumulative usage factor is calculated to be 0.18.

In conclusion, the proposed J-type PPSA can maintain structural integrity during the design lifetime. It may also be applicable to the KSNP, which has design conditions lower than those of the KNGR.

REFERENCES

[1] Kim, I. Y., Kim, B. S., Shin, T. M., Lee, M. W., and Lee, G. M., "Permanent Pool Cavity Seal Design Development," KAERI/RR-1053/91, Jan. 1991.
[2] ASME Boiler and Pressure Vessel Code, Section III, 1995 Edition.
[3] *ANSYS User's Manual for Revision 5.4*, Swanson Analysis System, Inc., 1997.
[4] Kim, M. G., "System Description for Reactor Cavity Pool Seal Assembly for KNGR," N0797-ME-SD912-00, KOPEC, May 1998.

Table 1 Comparison of Initial Value, Optimal Value, and Design Value for Design Parameters

Design Parameter	Initial Value (inches)	Optimal Value (inches)	Design Value (inches)
R	0.5	0.8159	0.8
T	0.2	0.1817	0.1875 (3/16)
L	5.0	6.9492	6.9
Maximum S.I.	199.41 ksi	183.40 ksi	183.41 ksi

Table 2 Maximum Stress Intensities for Each Service Loading Condition

Service Level	Load Combination	Max. Stress Intensity(ksi)	
		Elastic Analysis	Plastic Analysis
Level A	DW + TH	139.26	-
Level D	DW + TH + SSE	183.41	41.15
Refueling	DW + HP	28.61	-

Notes: 1) DW; dead weight, TH ; thermal load due to temperature difference,
HP; hydraulic pressure, IRWST ; in reactor water storage tank.
2) IRWST load is not considered in this paper due to trivial load.

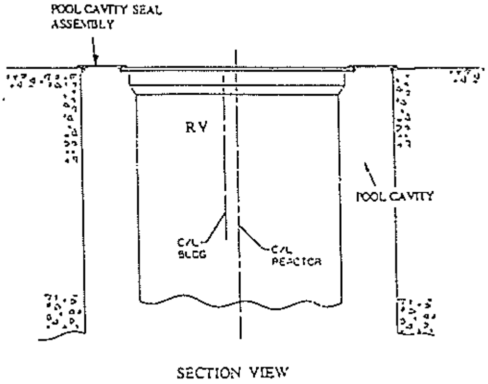


Figure 1 Position of Pool Seal Assembly in Reactor Building

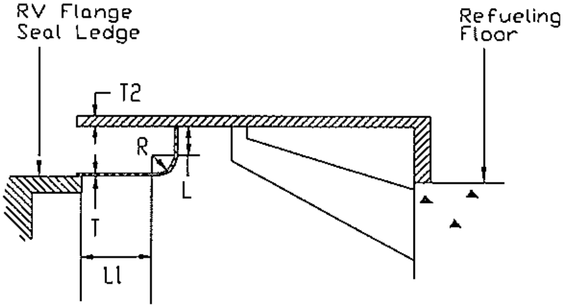
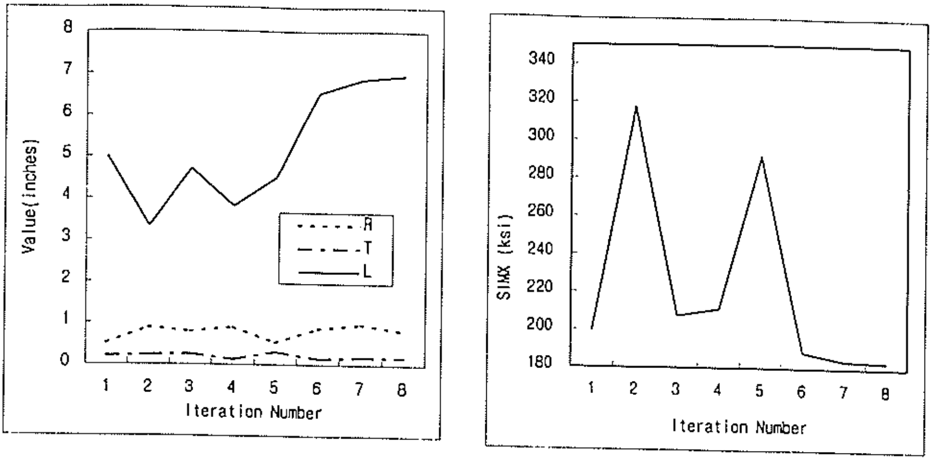


Figure 2 Design Parameters of PPSA with J-type Section



(a) Design Parameters

(b) Object Function (SIMX)

Figure 3 Variation of Design Parameters and Object Function during Optimization Process

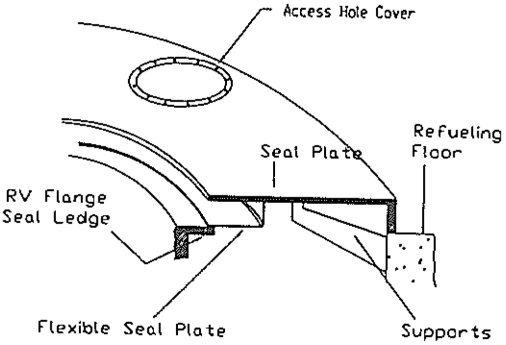


Figure 4 Sketch of Permanent Pool Seal Assembly Design

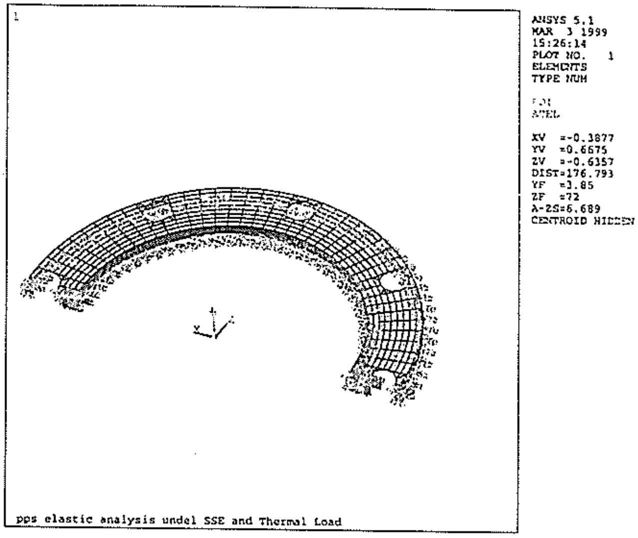


Figure 5 ANSYS Model for PPSA

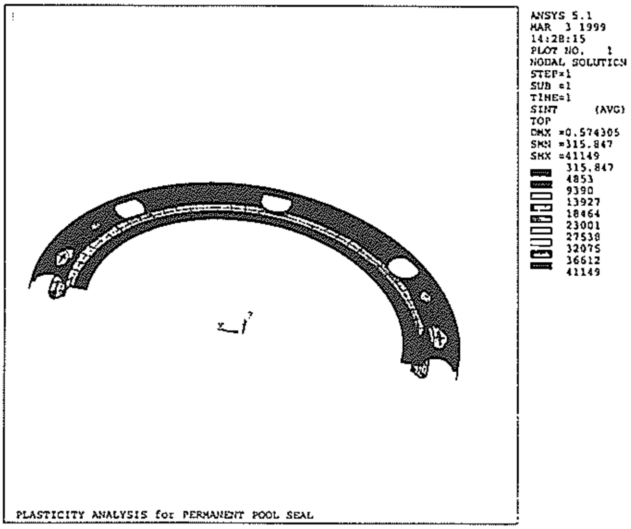


Figure 6 Result of the Plastic Analysis for PPSA (Level D Load)