Study on head loss evaluation for OPR1000 plant based on NUREG/CR-6224 methodology

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1. Introduction

Recirculation sump could be clogged by debris generated from high energy pipe line break accident and as a result, failure of safety injection and containment spray pumps could be invoked at recirculation cooling stage. This safety issue was assigned as GSI-191 and a lot of research works have been investigated to resolve this issue worldwide including Korea. In resolving the GSI-191 safety issue, three important elements to be quantified are a) amount of debris generated b) transport fraction of debris from break to the sump screen inlet and c) amount of head loss due to debris bed formed on the surface of sump screen. In the present study, we focus on the third element, that is, a quantification of head loss due to debris bed formed on the screen surface for the OPR1000 plant. For this, first, we reviewed previous research work on the head loss evaluation methodology and corresponding safety evaluation report. Then, based on review result, we developed an optimized head loss evaluation model specific to the OPR1000 plant. Finally, a head loss evaluation for the OPR1000 plant was performed and discussed.

2. Head Loss Evaluation Methodology

A pioneering research on head loss evaluation for sump clogging issue was NUREG/CR-6224[1] done by the US Nuclear Regulatory Commission (US NRC). After that, the US nuclear energy institute developed NEI 04-07 [2] methodology based on NUREG/CR-6224 [1]. For NEI 04-07 [2], the US NRC also published a safety evaluation report [3]. To identify the applicability of previous head loss methodology and conservative guidelines to the OPR1000 plant, previous head loss evaluation methodologies [1, 2] and corresponding safety evaluation report [3] are reviewed first.

2.1 NUREG/CR-6224 Head Loss Model

Basically, NEI 04-07 [2] head loss evaluation model is the same as that of NUREG/CR-6224 [1]. Therefore, only the NUREG/CR-6224 [1] head loss evaluation methodology is focused in the present study. NUREG/CR-6224 [1] methodology is based on the following head loss model.

$$\Delta H = \Lambda\left[3.5 S_v \alpha_m^{1.5}\left(1+57\alpha_m^3\right)\mu U + 0.66 S_v \alpha_m / (1-\alpha_m)\rho U^2\right]\Delta L_m \quad (1)$$

where ΔH is a head loss (ft-water), Λ is a conversion factor 4.1528×10^{-5}(ft-water/inch), S_v is a surface-to-volume ratio of debris (ft^{-1}), α_m is a solidity of mixed debris bed, μ is a dynamic viscosity of water (lbm/ft-sec), U is a screen approach velocity (ft/sec), ρ is a density of water (lbm/ft^3) and ΔL_m is mixed debris bed thickness (inch). Equation (1) combined with the following auxiliary equations forms complete set of relevant equations for the head loss determination.

$$\alpha_m = (1+\rho_f/\rho_p\,\eta)\alpha_o c_r,\ \ \alpha_m = 65/\rho_p \quad (2a, b)$$

$$c_r = 1.3\left(\Delta H/\Delta L_o\right)^{0.38} \quad (3)$$

where ρ_f and ρ_p are densities of fiber and particulate debris, respectively, η is a particulate to fiber mass ratio, α_o is a solidity of the original fiber blanket, c_r is a volumetric compression of debris($\equiv\Delta L_o/\Delta L_m$), ΔL_o is a theoretical fibrous debris bed thickness. For a head loss calculation at a design debris load, Eq. (1), (2a) and (3) are solved iteratively and for a head loss at thin bed effect load, Eq. (1) and (2b) are solved directly. Basically, the head loss model given above was developed and verified for a mixed debris bed made of fiber and particulate debris [1]. Therefore it can be also applied to the head loss evaluation of the OPR1000 plant with minor change if its debris bed composition is made of fiber and particulate debris.

2.2 Guideline for Conservative Head Loss Evaluation

For the application of the head loss model [1, 2], the US NRC suggested several guidelines [3]. To secure conservative head loss evaluation for the OPR1000 plant, we reviewed it thoroughly and identified some elements to be reflected in the present study. They are as follows:

- Since the surface-to-volume ratio (S_v) of particulate type debris is an uncertain variable which affects head loss severely, much of attention should be given to its determination.
- Since a limiting value of solidity (α_m) used in the head loss calculation at thin bed effect load and determined by Eq. (2b) has a large uncertainty, it should be determined properly for specific debris.
- A proper density value of latent particulate type debris is not $168 lbm/ft^3$ from plants survey result but $100 lbm/ft^3$ in conservative head loss terms.
- The best way to determine input parameters for the head loss evaluation is resort to the use of proper experiment results.

3. Head Loss Model Specific to OPR1000 Plant

Based on previous review results and additional conservative considerations, an optimized NUREG/CR-6224 [1] head loss model for the OPR1000 plant was developed and resulting head loss evaluation was performed in this section.

3.1 Optimized Head Loss Model

Debris generated by a high energy pipe line break and various materials in a nuclear power plant are likely to generate additional chemical precipitates combined with a chemical additive such as TSP. Since they work as additional debris source, they should be accounted for properly in the head loss evaluation model of the OPR1000 plant. For this, the head loss calculation of the vertical prototype strainer design load test for the OPR1000 plant [4] was performed by the NUREG/CR-6224 [1] head loss model assuming chemical precipitates as artificial particulate type debris. Through reducing the total amount of chemical precipitates from the original mass of 106.6lbm, an exact match of the head loss between the experiment and the calculation was identified when it reduces to 44.4lbm. From these calculations, it was verified that under the present artificial particulate type debris assumption for the chemical precipitates, an effective amount of chemical precipitate was a fraction of 0.417(=44.4/106.6) of the original total amount of chemical precipitates. In addition to consideration of chemical precipitates, one of the main advantages of this type of approach is to eliminate an uncertainty in the surface-to-volume ratio (S_v) of particulate type debris involved in the head loss calculation.

When a fiber bed of approximately one-eighth-inch thickness is formed and if there is sufficient particulate debris, a low permeability granular layer of debris on top of the fiber bed would be formed. Consequently, the head loss associated with this debris bed could be quite high, and surprisingly enough, greater than the head loss associated with much larger quantities of fiber and much thicker beds of debris. This apparently counterintuitive head loss phenomenon is known as the thin bed effect. It is well know that the head loss at the thin bed effect load is the most limiting one and as a result it should be evaluated without fail when head loss analysis applies. In NUREG/CR-6224 [1], head loss at the thin bed effect load is calculated with Eq. (2b) through which a maximum solidity of mixed debris bed is limited to 0.2 when the density of particulate type debris (ρ_p) is given by 324lbm/ft^3. However, as noted before (i.e. section 2.2), this equation contains a lot of uncertainty and its origin of uncertainty is that Eq. (2b) was derived for a particulate type debris such as BWR sludge. Therefore, in the present study, the maximum solidity of mixed debris bed required for the head loss evaluation of the OPR1000 plant at the thin bed effect load was estimated through an experiment directly.

For this, the vertical prototype strainer thin bed test data for the OPR1000 plant [4] was evaluated by the NUREG/CR-6224 [1] head loss model with varying the maximum solidity of mixed debris bed. From these evaluations, it was found that an exact match of the head loss between the experiment and the calculation was identified when the maximum solidity is given as 0.2522. That is, it is identified that the proper maximum solidity value of the OPR1000 plant is not 0.2 from NUREG/CR-6224 [1] but 0.2522.

3.2 Head Loss Evaluation for the OPR1000 Plant

The use of optimization results of NUREG/CR-6224 [1] model with reference to the proper experiment [4] was made for the evaluation of head loss of the OPR1000 plant at the design debris load and at the thin bed effect load with reference to following input parameters. Debris quantities considered in the head loss calculation of the OPR1000 plant at the design debris load are NUKON^{TM} (750ft^3), latent dirt-dust (200lbm), epoxy (30ft^3) and chemical precipitates (78.55lbm) [4]. For the head loss calculation at the thin bed effect load, only the quantity of NUKON^{TM} is reduced to 23.96ft^3 which corresponds to one-eighth-inch fiber bed thickness with other debris quantities are remained untouched. Use of maximum flow rate of two-train HPSI and LPSI pumps at the recirculation cooling stage is made and only one sump of the two is considered to maximize the screen approach velocity. Water temperature at sump is assumed to be 140^{o}F due to SPIRT resolution. Densities of NUKON^{TM} and latent particulate type debris are considered as 159lbm/ft^3 and 100lbm/ft^3, respectively for conservatism. 2,300ft^2 screen area was made for each sump [4].

Based on above parameters, resulting evaluation shows that the head losses are 0.88ft-water and 3.11ft-water at the design debris load and the thin bed effect load, respectively. It is also verified that the head loss of the thin bed case is much larger than that of the design load. That is, the limiting head loss of sump screen is due to the thin bed effect load. Much of calculation procedures and limitations of the present study can be found in a KINS report [5] in detail.

4. Conclusions

Through peer review on the previous head loss evaluation methodology, its applicability to the OPR1000 plant is identified. The use of proper experimental result is made for the development of the optimized head loss model suitable for the OPR1000 plant evaluation and the resulting model combined with conservative guidelines is applied to determine quantitative head loss of the OPR1000 plant for the design debris load and the thin bed effect load cases. Resulting calculation shows the thin bed effect load gives the most dominating head loss for the sump screen.

Analytical head loss evaluation methodology developed here also can be used for the safety review of sump design of domestic nuclear power plants.

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