

Evaluation of Off-Design Safety Margins for the Nuclear Power Plant ESW-CCW Cooling System under Rising Seawater Temperatures Using Flowmaster

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1. Introduction

Most of the excess heat accumulated in the Earth's climate system due to anthropogenic greenhouse gas emissions has been absorbed by the oceans. The Intergovernmental Panel on Climate Change (IPCC) has assessed that the global ocean has undergone sustained warming since 1970 and that marine heatwaves have increased in both frequency and intensity [1]. These changes can alter the thermal conditions of coastal waters used as intake sources for nuclear power plants, thereby reducing the operating margin of their cooling systems. In nuclear power plants that use seawater as the ultimate heat sink, heat generated by auxiliary and safety-related components is collected through the Component Cooling Water (CCW) system and subsequently transferred to the Essential Service Water (ESW) system. As the ESW inlet temperature increases, the effective temperature difference between the two fluids decreases. Consequently, under the same heat exchanger conditions, the CCW outlet temperature may increase or a higher cooling-water flow rate may be required. The International Atomic Energy Agency (IAEA) has reported that elevated cooling-water temperatures can affect heat removal performance and electricity generation at nuclear power plants, potentially resulting in operational restrictions such as power derating or plant shutdown [2]. For example, Millstone Unit 2 in the United States was derated and subsequently transitioned to Hot Standby after the Ultimate Heat Sink (UHS) temperature exceeded the Technical Specification limit [3]. In Korea, cases have also been reported in which intake seawater temperatures approached operational limits [4]. However, existing assessments have generally focused on plant-specific temperature criteria and response measures, and comparative evaluations of system responses under normal operating and Design Basis Accident (DBA) conditions over the same seawater temperature range remain limited. In this study, a Flowmaster model of the ESW-CCW cooling system was developed based on the Final Safety Analysis Report (FSAR) for Hanul Units 5 and 6 [5]. Changes in the CCW outlet temperature and system flow rates with increasing ESW inlet temperature were compared under normal operating and DBA conditions. In addition, the effects of increasing the number of heat exchanger plates on the safety margin and the limiting ESW inlet temperature were evaluated.

2. Methodology

The ESW-CCW cooling system was modeled based on the system configuration and design conditions specified in the FSAR for Hanul Units 5 and 6 [5]. As shown in Fig. 1, the model consisted of a heater representing the heat load of the cooled components, a CCW pump, and two heat exchangers connected in parallel. The ESW supplied by the pump was divided between the cold sides of the two heat exchangers, and the outlet flows from the heat exchangers were subsequently combined and discharged. In Fig. 1, the heat exchangers, pumps, and heat source are highlighted in blue, red, and green, respectively, where the heat source represents the increase in water temperature resulting from containment spray cooling. The flow path and major equipment configuration were identical under normal operation and DBA conditions; therefore, Fig. 1 presents the DBA case as a representative model, with the two operating conditions distinguished by their corresponding heat-load inputs rather than by changes in the system configuration.

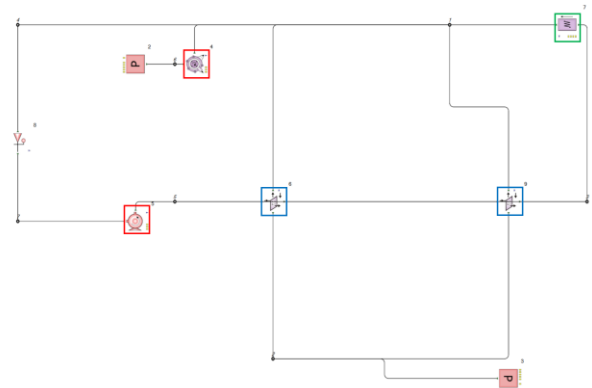


Fig. 1. Flowmaster model of the CCW and ESW in DBA case.

In Fig. 1, the CCW heat load was represented by summing the heat loads of the individual cooled components and applying the total as an equivalent input to the heater. The ESW inlet temperature was varied from 20 to 40°C in 1°C increments, with the FSAR design upper limit of 32.4°C included as an additional comparison point. The flow rates for each condition were not prescribed but were determined at the operating point established by the pump performance and system

pressure losses. Under the baseline DBA condition, the calculated total ESW flow rate differed from the design flow rate by approximately 0.13%, confirming agreement with the reference operating point. However, because detailed pump curves and performance data for individual components are limited in publicly available sources, the analysis was intended to evaluate relative changes in system response and safety margin with respect to the baseline condition rather than to provide a licensing-level validation of absolute system performance. To evaluate the effect of improving heat exchanger performance, the number of heat exchanger plates was increased by 10%, 20%, 30%, 40%, and 50% relative to the baseline configuration. The heat load, pump settings, and boundary conditions were maintained unchanged for all cases except for the number of plates.

3. Safety Margin Evaluation Method

The system safety margin was evaluated as the difference between the allowable CCW heat exchanger outlet temperature of 43.3°C specified in the FSAR and the calculated outlet temperature. A calculated CCW outlet temperature below 43.3°C was considered to satisfy the acceptance criterion. The ESW inlet temperature at which the CCW outlet temperature reached 43.3°C was defined as the limiting ESW inlet temperature.

4. Results and Discussion

Figures 2 and 3 show the variation in CCW outlet temperature with ESW inlet temperature under normal operation and DBA conditions, respectively. The results for the baseline heat exchanger and the increased plate configurations are presented together. The FSAR CCW outlet temperature criterion of 43.3°C and the design upper limit of the ESW inlet temperature of 32.4°C are also indicated as reference conditions.

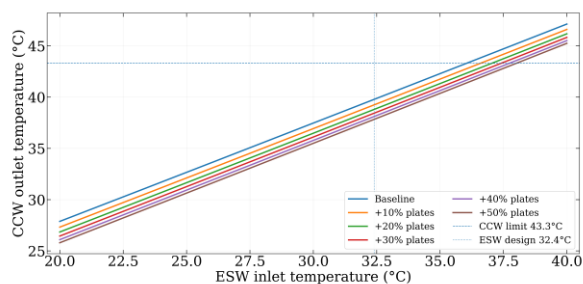


Fig. 2. CCW outlet temperature according to ESW inlet temperature under normal operation.

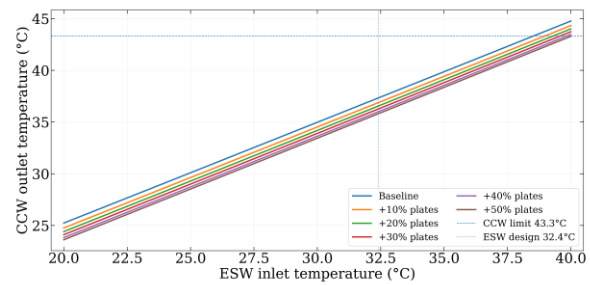


Fig. 3. CCW outlet temperature according to ESW inlet temperature under DBA conditions.

For both operating conditions, the CCW outlet temperature increased nearly linearly with increasing ESW inlet temperature. At an ESW inlet temperature of 32.4°C, the baseline heat exchanger yielded CCW outlet temperatures of 39.79°C under normal operation and 37.32°C under DBA conditions. The corresponding safety margins to the FSAR criterion of 43.3°C were 3.51°C and 5.98°C, respectively. The limiting ESW inlet temperature at which the CCW outlet temperature reached 43.3°C was 36.04°C under normal operation and 38.51°C under DBA conditions. This difference resulted from the larger heat load imposed on the CCW system under normal operation than under the selected DBA condition. The higher heat load increased the temperature rise of the CCW loop, resulting in a higher CCW outlet temperature and, consequently, a smaller margin to the 43.3°C criterion. In both cases, increasing the number of heat exchanger plates reduced the CCW outlet temperature, indicating improved heat removal capability under elevated seawater temperature conditions.

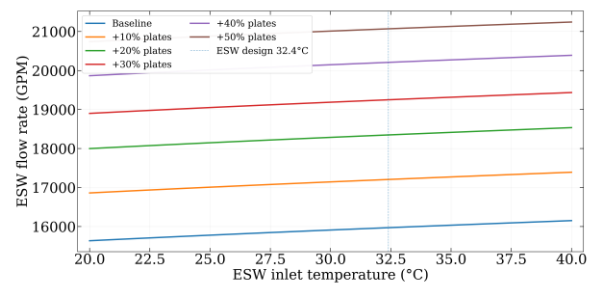


Fig. 4. ESW flow rate according to ESW inlet temperature and heat exchanger plate increase under DBA conditions.

Figure 4 shows the variation in ESW flow rate with ESW inlet temperature and heat exchanger plate increase under the DBA condition. The ESW flow rate increased gradually with increasing inlet temperature for all heat exchanger configurations. For the baseline heat exchanger, the flow rate increased from 15,635 GPM at 20°C to 16,151 GPM at 40°C, corresponding to an increase of approximately 3.30%. The operating flow rate also increased with the number of heat exchanger plates. At an ESW inlet temperature of 32.4°C, the ESW flow rate increased from approximately 15,970 GPM for the baseline case to 21,070 GPM for the +50% plate case.

Meanwhile, the relative increase in ESW flow rate over the 20–40°C range decreased as the number of plates increased. Overall, increasing the number of heat exchanger plates reduced the CCW outlet temperature and improved the thermal margin under elevated seawater temperature conditions. However, the corresponding ESW operating flow rate increased, indicating that changes in heat exchanger configuration affect both thermal performance and system hydraulic behavior. Therefore, heat exchanger enhancement should be evaluated by considering the improvement in thermal margin together with changes in system operating conditions.

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