Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 24-25, 2024

Considerations on Design Changes of the Shutdown Cooling System for Advanced Power Reactor 1000

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***Keywords:** APR1000, APR1400, EUR, SCS*

1. Introduction

The APR1400, a 1400 MW Advanced Power Reactor developed using domestic technology, has proven its economics efficiency and safety. This is evident from the successful construction of Saeul Units 1 and 2 and the completion of all four units of the Barakah Nuclear Power Plant in the UAE

With Europe's nuclear market growing due to power shortages and a push for green energy, it is crucial to obtain the European Utility Requirements (EUR) certification. This paper study the necessary design changes to adapt the APR1400 to a 1000 MW class reactor. Specifically, it focuses on modifications to the Shutdown Cooling System (SCS) to meet EUR standards and boost competitiveness in the European market.

2. Design Change Requirements and Improvement Strategies

2.1 Modification of System Configuration and Functions

The SCS and the Containment Spray System (CSS) in the APR1400 are each configured in two trains, adhering to the single-failure criterion. EUR stipulates the need for on-line maintenance, requiring additional system redundancy. Therefore, to meet these requirements, the SCS and CSS need to be reconfigured from two trains to three trains each, totaling six trains. This would, however, lead to significant increases in construction costs. After comprehensive analysis, it was determined that configuring the SCS in four trains and incorporating the CSS function would be more feasible. The CSS is required only during operating modes 1, 2, and 3, while the SCS is applicable during modes 4, 5, and 6, thus dual functionality poses no design issues. Although configuring the systems in three trains could meet the on-line maintenance concept, it would necessitate a larger containment building, thereby significantly increasing construction costs. Consequently, a four-train configuration was finalized after discussions among stakeholders.

2.2 Exclusion of Shared Devices Among Safety Systems

The EUR mandates the exclusion of shared devices among safety systems. In the APR1400, the discharge piping of the Safety Injection System (SIS) passes through three serially arranged check valves and connects to the Reactor Coolant System (RCS) via DVI nozzle to the reactor vessel. The SCS, to reduce construction costs, is connected upstream of the check valves of the SIS, violating EUR requirements. Therefore, the APR1400 SCS discharge must be redesigned to connect to the cold leg, instead of the DVI nozzle to the reactor vessel.

2.3 Design Criteria of EUR for the Shutdown Cooling System

EUR requires the SCS to have the capability to remove decay heat, the sensible heat of the reactor coolant, the heat generated by the SCS pumps, and the heat generated by the reactor coolant pumps during cooling to refueling temperature. The current design of the APR1400, based on U.S. regulatory requirements, does not include the removal of reactor coolant pump heat. Therefore, the following modifications are necessary:

- ✓ The SCS should be capable of removing all specified heat sources.
- ✓ A reevaluation of the heat removal capacity of existing SCS components to ensure compliance with EUR requirements.

2.4 Difference of Design Criteria between APR1400 and APR1000

SCS design criteria of APR1400 for Saeul Unit 1 and 2 is as following [2]:

(1) to 60°C (140°F) – within 24 hours after reactor Shutdown
(2) to 54.4°F (130°F) – by the reactor vessel head stud de-tensioning operation start (within 40 hours after reactor shutdown)
(3) to 48.9°F (120°F) – within 96 hours after reactor shutdown

SCS design criteria of APR1000 is as following [1]:

(1) to 60°F (140°F) – within 24 hours after reactor shutdown

(2) to 54.4°F (130°F) – by the reactor vessel head stud de-tensioning operation start
(3) to 48.9°F (120°F) – within 96 hours after reactor shutdown (included duration of removal time for reactor vessel head)

2.5 Backup System for Loss of the SCS

The EUR stipulate the incorporation of redundant systems to mitigate the risk of common cause failures that may lead to a total loss of the SCS. To comply with these requirements, the Diverse Containment Spray System (DCSS) has been adopted. The DCSS is integrated into the SCS operational flow path, as depicted in Fig.1. This system serves as an alternative cooling mechanism, ensuring the continuous removal of decay heat under failure scenarios.

2.6 Description of analysis code, SOCOOLER

The SOCOOLER code shall have the capability to analyze the capacity for SCS to bring the reactor coolant average temperature and to analyze that the SCS shall be capable of cooling the pant with no component failures or a loss of two or three trains out of four trains in service. The basic purpose of shutdown cooling process using the SCS is to transfer the decay of the primary loop to the secondary loop. Once the key process parameters such as SCS initiation conditions, RCS volume and the effective heat transfer area, heat transfer rate and resistance coefficient of heat exchanger and pump mini-flow heat exchanger are identified as the input parameters for the SOCOOLER code.

2.7 Analysis Results of APR1000 SCS

Incorporating the design modifications specified in Sec. 2.1 to 2.5, the performance of the SCS was simulated using the SOCOOLER computational analysis code. This analysis aimed to verify the system's adherence to the EUR.

The analysis results is as following:

(1) to 60°F (140°F) – within 24 hours after reactor shutdown
(2) to 54.4°F (130°F) – by the reactor vessel head stud de-tensioning operation start (within 36 hours after reactor shutdown)
(3) to 48.9°F (120°F) – within 72 hours after reactor shutdown (included duration of removal time for reactor vessel head)

3. Conclusions

This study has identified and evaluated the necessary design modifications for the APR1000 to meet European Utility Requirements (EUR) and thereby enhance its suitability and competitiveness in the European nuclear market. The implementation of these design changes will not only ensure compliance with EUR but also improve the overall economic and operational feasibility of the reactor. The key design changes are summarized as follows:

Increase in System Trains and Functions: To meet EUR, the APR1000 SCS need to be reconfigured from two trains to four trains. This change addresses the on-line maintenance requirement and ensures redundancy, thus enhancing the system's reliability and safety. The dual-functionality approach, where the SCS incorporates CSS functions, optimizes system design without compromising operational integrity.

Exclusion of Shared Devices Among Safety Systems: EUR to eliminate shared devices among safety systems necessitates a significant redesign of the SCS. The current APR1400 design, which shares components between the SIS and the SCS, must be modified. The SCS discharge should be redirected to the cold leg of the RCS, ensuring compliance with EUR and enhancing system independence and safety.

Difference of SCS Design Criteria: The APR1000 must be capable of removing not only decay heat and the sensible heat of the core but also the heat generated by both the SCS pumps and the Reactor Coolant Pumps (RCP). This comprehensive heat removal capability is critical for EUR certification. Revising the design criteria and reevaluating the heat removal capacity of the existing components will ensure the system's adequacy under all operational conditions.

Satisfaction of EUR Design Criteria: The analysis results of APR1000 SCS using the SOCOOLER was showed to satisfy the EUR design criteria. By meeting the EUR, the APR1000 not only ensures compliance with the highest safety standards but also demonstrates a commitment to operational excellence and economic efficiency. These factors will significantly enhance the market viability and attractiveness in the European nuclear industry.

In conclusion, the identified design modifications for the APR1000 not only ensure compliance with EUR but also enhance the reactor's overall safety, reliability, and market competitiveness. These efforts position the APR1000 as a leading choice for future nuclear power generation projects, contributing to a safer and more sustainable energy future.

REFERENCES

[1] European Utility Requirements for LWR Nuclear Power Plants, Rev.E, December 2016.
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