Nuclear Engineering and Technology 57 (2025) 103127

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Enhancing equipment qualification testing facility for nuclear power plants: Achieving rapid temperature and pressure increase during design basis events

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ARTICLE INFO

Keywords:
Equipment qualification
Design based event
Loss of coolant accident
Class 1E
Superheated steam

ABSTRACT

The present study focuses on the development of an equipment qualification (EQ) testing facility for Class 1E equipment in nuclear power plants (NPPs), emphasizing the need to ensure safety functions under design basis events (DBEs). The Republic of Korea (ROK) has implemented international safety standards to support large NPP projects, necessitating the development of domestic EQ testing facilities to reduce the dependence on foreign facilities. To address this need, herein, a specialized facility capable of simulating harsh DBE conditions that may occur in NPPs in ROK was constructed. Through exhaustive research, target temperature and pressure profiles were developed for pressurized water reactors, and a superheated steam injection technique was devised for rapid temperature and pressure changes. The present study contributes to the advancement of domestic EQ testing capabilities, achieving up to 230 °C and 700 kPa within 30 s.

1. Introduction

Class 1E equipment [1,2] used in nuclear power plants (NPPs) refers to electrical equipment and systems essential for emergency reactor shutdown, containment isolation, reactor core cooling, containment, and reactor heat removal. Class 1E equipment should perform its safety function(s) without experiencing common-cause failures before, during, and after design basis events (DBEs), which are events used in the design to establish acceptable performance requirements for the structure, systems, and components. Equipment qualification (EQ) consists of demonstrating these capabilities of the equipment with reasonable assurance [3,4].

The Institute of Electrical and Electronics Engineers (IEEE) has established standards 323 and 344 [1,2], which provide technical guidance and methods for EQ of Class 1E equipment in DBE conditions. According to the standard, equipment is assessed using a type test and analysis. Analysis alone cannot be used for EQ [1], and in most cases, qualification through type test is required because electrical devices invariably contain nonmetallic components [5,6]. In the type test, the tested sample is aged to ensure that the equipment performs its safety-related functions at the end of its design life; aging is usually attained through thermal aging, radiation aging, wear, and vibration aging [7–9]. For equipment treated under end-of-design-life conditions, DBEs such as radiation accidents, earthquakes, and loss of coolant accidents (LOCAs) are simulated considering the accident conditions. The results show whether the assessed equipment can perform safety-related functions before, during, and after the DBEs.

The IEEE standards mandate that all safety-related equipment for which a qualified life or conditions has been established must be tested to demonstrate with reasonable assurance that it can perform its safety functions without experiencing common-cause failures before, during, and after applicable DBEs. Test facilities that can simulate DBE conditions such as LOCA on equipment specimens and monitor whether the specimens perform safety-related functions are essential for the construction of NPPs and the development of Class 1E equipment. In 2012, the Republic of Korea (ROK) implemented regulations based on IEEE standards 323 and 344 [1,2], underscoring the importance of EQ in the country's pursuit of the development of large NPP projects, mainly the Advanced Pressurized Reactor-1400 (APR-1400), for domestic construction and overseas exports.

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https://doi.org/10.1016/j.net.2024.07.058
Received 24 October 2023; Received in revised form 15 July 2024; Accepted 28 July 2024
Available online 31 July 2024

Table 1
LOCA DBE profiles for NPPs in ROK [8].

NPP	Maximum Temperature [°C]	Maximum Pressure [kPa]
NPP A2	157.78	308.89
NPP A3, A4	173.89	413.69
NPP B2, B3, B4	150.00	400.24
NPP C1, C2	173.89	413.69
NPP C3, C4	182.22	372.32
NPP C5, C6	182.22	393.00
NPP D1, D2	156.00	388.86
NPP D3, D4	182.22	393.00
NPP D5, D6	182.22	393.00

The steady demand for large NPPs in ROK necessitates the design and construction of domestic EQ testing facilities to eliminate the dependence on foreign facilities and overcome potential obstacles to exports. Therefore, the present study aimed to construct a specialized facility for EQ testing in DBE conditions. Such a facility must reproduce the required temperature and pressure representative of harsh environments encountered during DBEs in all existing NPPs in ROK.

To achieve this goal, we developed target temperature and pressure profiles for ROK's large pressurized water reactors through exhaustive information gathering. Additionally, a superheated steam injection technique was proposed to enable rapid changes in temperature and pressure during testing. All experimental results were rigorously verified through simulations in MARS-KS, a computational tool for modeling the thermal-hydraulic behavior of NPP systems. Notably, this work contributes to the improvement in EQ testing capabilities by enabling the increase in the temperature and pressure in the test chamber up to 230 °C and 700 kPa, respectively, within 30 s.

The contents of this paper are organized as follows. Section 2 outlines the target test conditions for the LOCA DBE test facility. Section 3 details the Phase-I experiments with MARS validation. Section 4 provides a discussion of Phase-II experiments as a solution to the research problem. Section 5 summarizes the key findings and provides the concluding remarks.

2. Target test conditions for the LOCA DBE test facility

To test whether equipment performs safety-related functions before, during, and after DBEs, an experimental test facility that can reproduce the actual LOCA DBE conditions is required.

This section describes the process of securing the necessary standard profiles to build a test facility that simulates a LOCA environment during a DBE on an NPP [10]. Subsequently, we provide the test facility configuration and describe the actual facility installed to evaluate the operability of equipment exposed to the LOCA DBE environment.

2.1. LOCA DBE test profiles

The development of a LOCA DBE experimental test facility requires the elaboration of a test standard profile that includes all LOCA DBE profiles of existing NPPs. Therefore, we conducted a preliminary study of the LOCA DBE profiles of installed and operating NPPs, as shown in Table 1 [8]. Table 1 was developed based on technical specifications for 18 NPPs in ROK. These correspond to the containment conditions in the NPPs when a DBE occurs.

As shown in Table 1, the NPPs with the highest maximum temperature in the LOCA DBE Profile are NPPs C3, C4, C5, C6, D3, D4, D5, and D6 at 182.22 °C, and the NPPs with the highest maximum pressure are NPPs A3, A4, C1, and C2 at 413.69 kPa. Therefore, based on the LOCA DBE profiles of the existing NPPs, the profile used in the proposed LOCA DBE experimental test facility should reach the temperature and pressure of at least 182.22 °C and 413.69 kPa.

During LOCA DBE, the temperature and pressure rapidly increase in the early stages of the accident, after which high temperature and pressure are maintained for a certain period. Then, during the chemical spraying, the temperature is lowered once, followed by a slow decrease in temperature and pressure over a long period. Graphical representations of the overall changes in conditions are shown in Figs. 1 and 2.

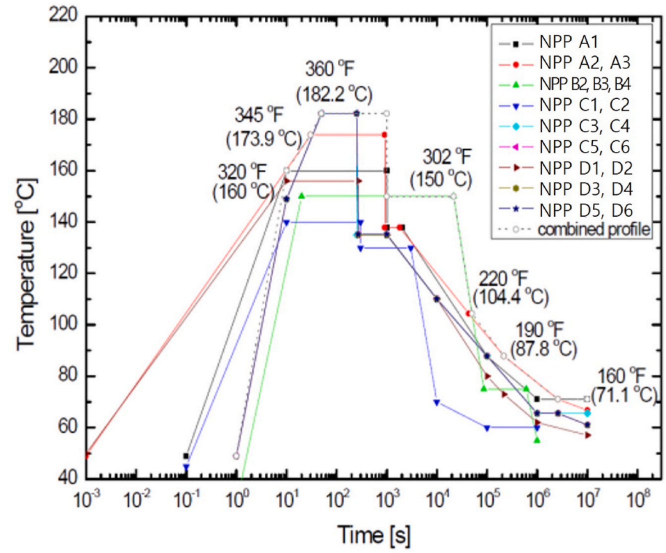

Fig. 1. LOCA DBE profiles: Temperature.

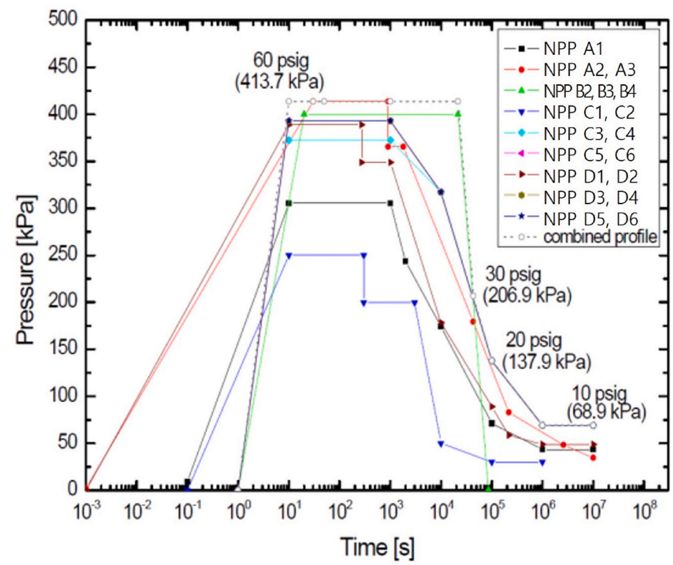

Fig. 2. LOCA DBE profiles: Pressure.

As shown in Figs. 1 and 2, the initial rapid-heating zone, where temperature and pressure rise most steeply, typically forms around the first 10 s of an incident. The high-temperature, high-pressure environment is then maintained for more than 100 s, and around 1000 s, chemical spraying is performed to rapidly reduce the temperature and pressure. After the chemical spraying, the temperature and pressure gradually decrease to normal values.

Therefore, herein, we propose a LOCA DBE standard testing profile that covers the profiles in Figs. 1 and 2. Furthermore, we constructed an experimental LOCA DBE test facility and tested it for the capability to reproduce the proposed profile.

2.2. Configuring the LOCA DBE experimental test facility

To build an experimental test facility for reproducing the LOCA DBE

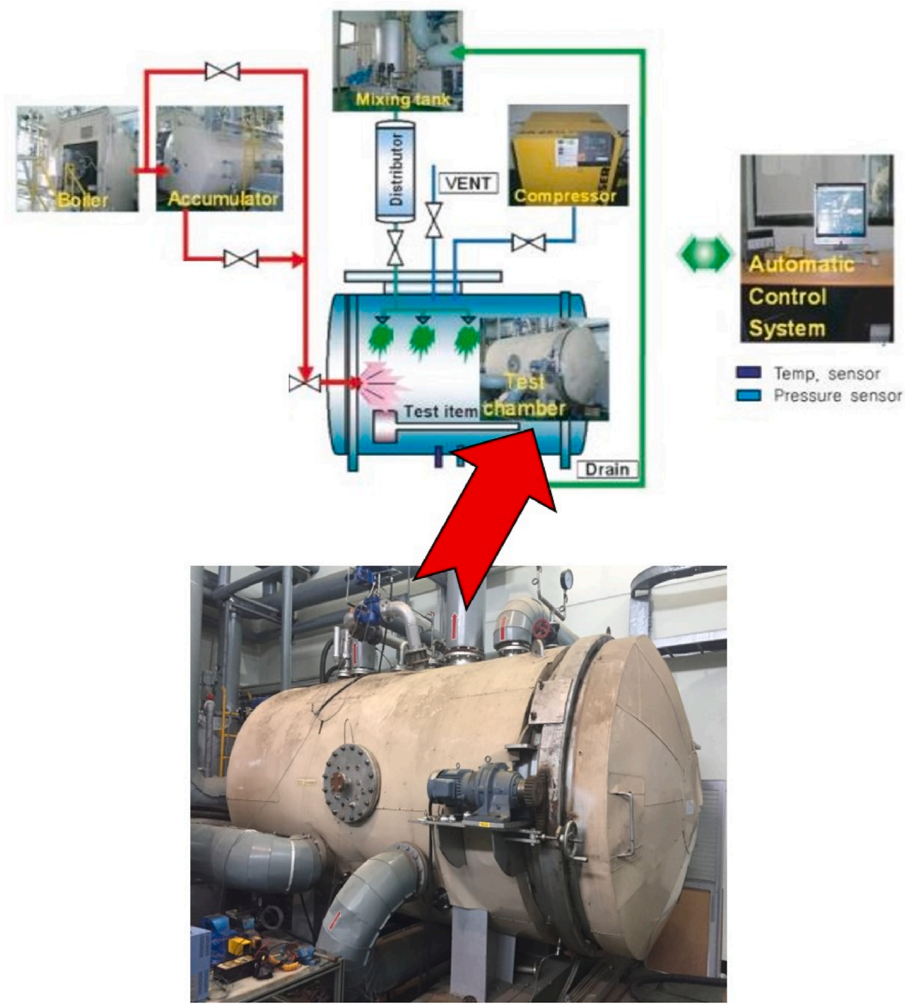

Fig. 3. Schematic and photos of the LOCA DBE experimental test system.

environment, we considered several critical systems.

The first is the heat supply system. The heat supply system uses steam as the working fluid and includes an accumulator to increase the temperature and pressure of steam.

The second is the chemical spray system. Chemical spraying for neutron absorption is responsible for rapidly reducing the temperature and pressure in the LOCA DBE environment. To achieve this, the chemical spray system was configured to ensure that a sufficient amount of chemical is sprayed.

The third is an automatic control system. The first and second systems must be configured to ensure appropriate operation. Thus, the control system was configured to control heat supply and cooling to maintain the environment according to the test profile.

The fourth is the chamber system where the LOCA DBE tests are performed. The chamber system contains sensors that measure the temperature and pressure. In a LOCA DBE experimental test facility, the three systems must accurately implement the desired environment in the chamber system.

Fig. 3 below shows a diagram of the four systems described above.

Fig. 3 shows the photos of the constructed experimental test facility. This facility was experimentally tested for the capability to reproduce the desired environment according to the standard profile proposed herein.

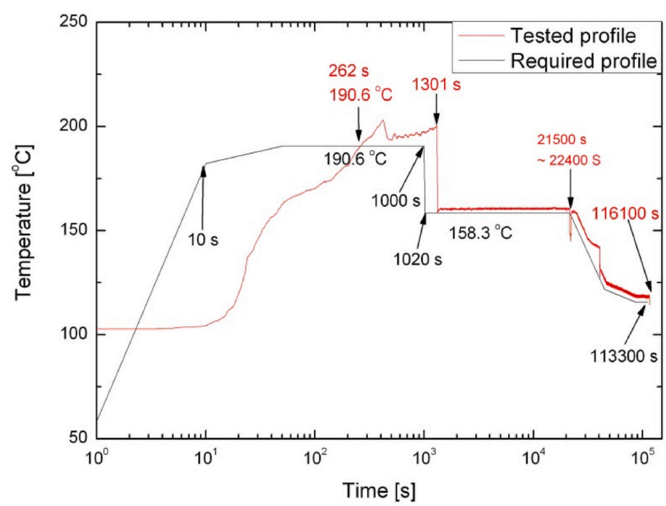

Fig. 4. LOCA DBE experimental test results: Temperature.

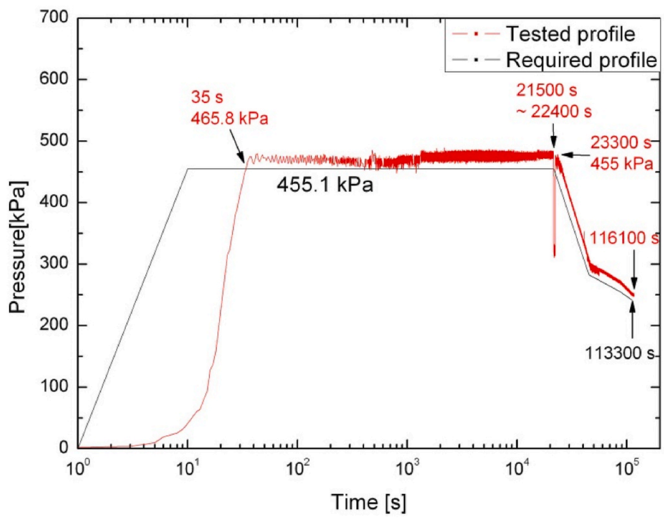

Fig. 5. LOCA DBE experimental test results: Pressure.

3. Phase-I: initial testing of the LOCA DBE experimental test facility

3.1. Experimental testing results

The initial conditions of the steam supplied to the chamber are a temperature of 170°C-180 °C and a pressure of 850–900 kPa. For the first 10 s of the test, both the inlet and outlet valves remained open. From 10 to 300 s, when the initial temperature and pressure of the standard profile were reached, the valves at the chamber outlet began to automatically control pressure according to the standard profile. Between 300 and 1300 s, the valve at the inlet maintained a flow rate of 5%–20 % to comply with the temperature and pressure conditions of the standard profile, while the valve at the outlet performed the same automatic control as before. As the purpose of this test was to verify that the environment inside the chamber follows the standard profile well, the flow rate of the supplied steam was not measured. The test was refined to measure the flow rate separately, as described in Section 4.

The results of the experimental test using the LOCA DBE experimental test facility are plotted in Figs. 4 and 5 below.

Black lines in Figs. 4 and 5 represent the temperature and pressure of the standard profile, respectively, and the red lines are the actual measured temperature and pressure in the test chamber.

In the standard profile, the temperature and pressure are supposed to rise sharply in the first 10 s and then remain constant. However, the temperature in the test chamber remains steady at around 100 °C for the first 10 s, increases relatively slowly between 10 and 100 s, and reaches the target temperature only at 262 s. Similar to temperature, pressure gradually increases in the first 10 s, after which it sharply increases, reaching the target at 35 s.

To elucidate the reason for the slow temperature increase, which is well beyond the target 10 s in the standard profile, we performed simulations for temperature in MARS-KS using the same equipment and conditions.

3.2. Code Benchmarking on a LOCA DBE test facility

The computer simulation of the LOCA DBE test facility was performed using a one-dimensional thermal-hydraulic system, MARS-KS 2.0. MARS-KS has been developed by the Korea Atomic Energy Research Institute [11] based on RELAP5/MOD3.2 [12]. It numerically solves one-dimensional two-phase flow problems using six equations with mass, momentum, and energy conservation equations. This software is currently managed by the Korea Institute of Nuclear Safety to ensure that it remains the state-of-the-art technology implementing heat transfer, noncondensable gas behavior, pressure drop, and critical heat flux.

The hydrodynamic system of the LOCA DBE test facility was nodalized into two time-dependent volumes, three pipes, and one branch component, as shown in Fig. 6. Component “time-dependent volume” #301 provides the superheated or saturated pressurized steam. Injection flow is managed by component “Valve” #450. When the temperature of component “pipe” #200-2 is higher than 190 °C, the flow surface of #450 is closed. Component “branch” #400 distributes steam into the chamber through three single junctions 411, 412, and 413. Three pipes

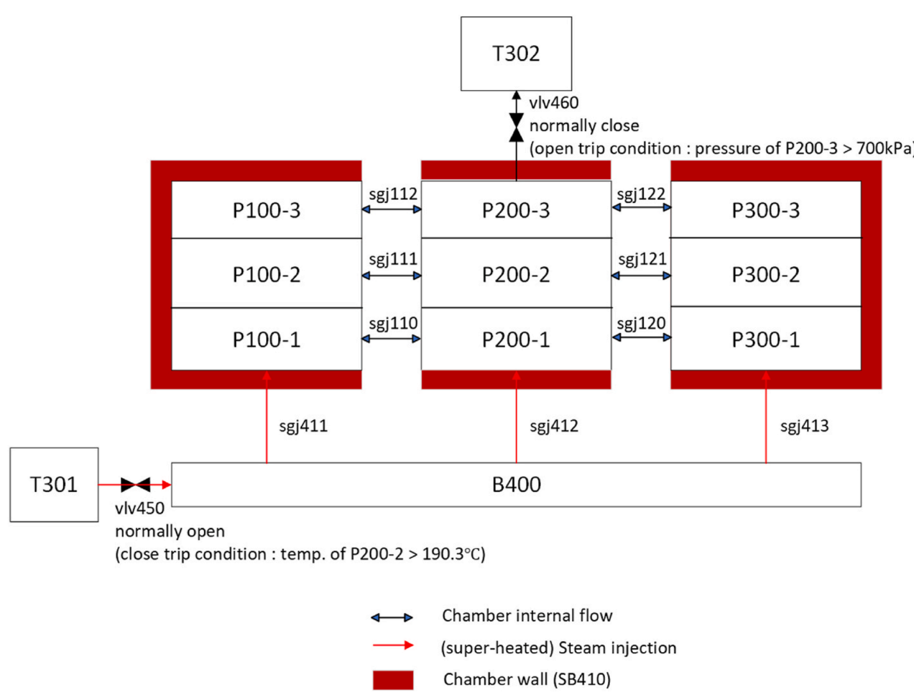

Fig. 6. Nodalization in the MARS-KS simulation.

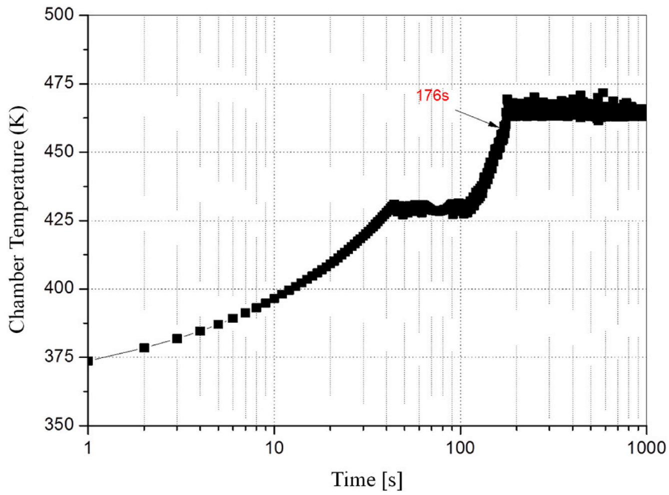

Fig. 7. MARS simulation results: Temperature.

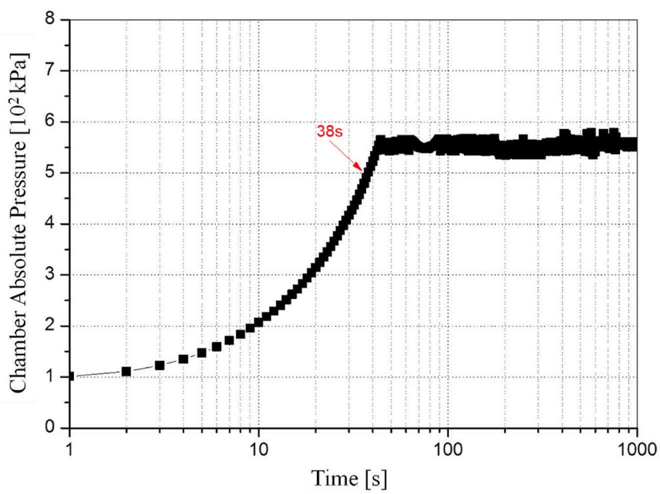

Fig. 8. MARS-KS simulation results: Pressure.

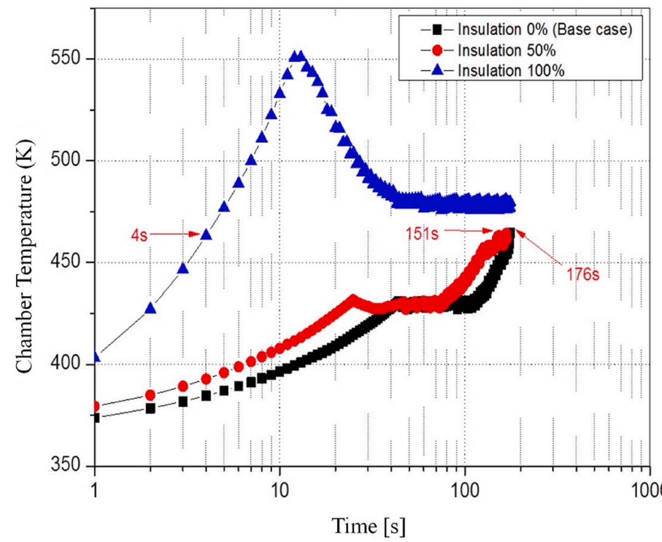

Fig. 9. MARS-KS simulation results with chamber insulation: Temperature.

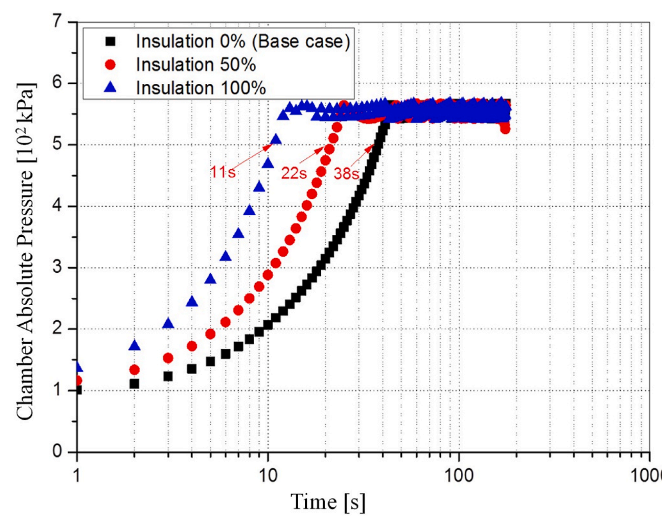

Fig. 10. MARS-KS simulation results with chamber insulation: Pressure.

have cross flows with their neighbors using single junctions 110–112 and 120–122. When the pressure of pipe #200 vol 3 reaches 500 kPa, valve 460 opens and steam flows to component "time-dependent volume" #302.

The MARS-KS simulation results are shown in Figs. 7 and 8. In Fig. 7, which shows the temperature, a profile similar to that obtained in the actual experimental test is observed, with no significant changes in the first 10 s, followed by a gradual increase, a plateau at 150 °C, and further temperature increase, reaching the target value at 176 s. In Fig. 8, which shows the pressure results, no significant changes are observed in the first 10 s, after which the temperature sharply rises, reaching the target at 38 s.

The results in Figs. 7 and 8 show profiles very similar to those obtained in the LOCA DBE experimental test described in Section 3.1. This indicates that the MARS-KS simulation is a good implementation of the LOCA DBE experimental test facility in Section 2.2.

3.3. Limitations of LOCA DBE experimental test facility

Although the developed simulation model of the constructed LOCA DBE experimental facility (Section 2.2) accurately predicts its behavior, the experimental facility itself does not track the initial rapid changes in the standard profile well.

Based on the experimental and simulation results, we concluded that the temperature did not rise as fast as required because of the contact between the steam, which is the working fluid, and the inner wall of the chamber, which takes away a substantial amount of the thermal energy of the steam. The temperature starts to rapidly increase only when the thermal equilibrium between the steam and the chamber is reached. We verified this hypothesis through simulations in MARS-KS with insulation added to the chamber.

Figs. 9 and 10 above show the MARS-KS simulation results (temperature and pressure, respectively) for different degrees of internal insulation of the chamber.

As shown in Figs. 9 and 50 % insulation reduces the time within which the temperature reaches a steady state by about 25 s. At the same time, 100 % insulation dramatically speeds up the initial change in temperature. The pressure results in Fig. 10 show that, similar to the temperature results, the better the insulation, the shorter the initial rapid change period.

These results suggest that when the steam supplied to the chamber meets the inner wall of the chamber, it loses thermal energy to reach thermal equilibrium with the inner wall of the chamber. As a result, the increase in temperature and pressure in the chamber is delayed until the inner wall of the chamber reaches thermal equilibrium with the supplied steam. Therefore, it would be appropriate to insulate the inner wall of

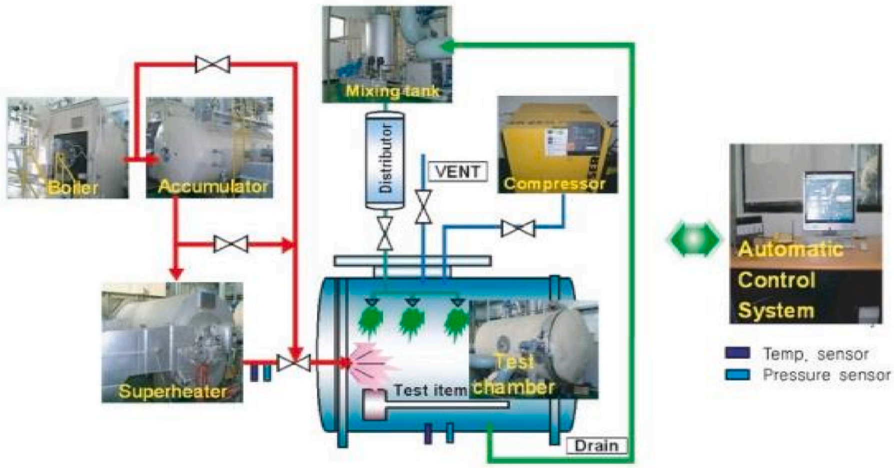

Fig. 11. Schematic of the modified LOCA DBE experimental test facility.

the chamber, but this is technically difficult.

As an alternative, we propose increasing the thermal energy of the steam and injecting it into the chamber. The experimental test facility was modified by adding a superheater to the heat supply system to provide additional thermal energy to the steam. The superheater was connected to the automatic control system to increase the temperature and pressure according to the standard profile.

4. Phase-II: modification of LOCA DBE experimental test facility

4.1. Design modification: addition of a superheater

Fig. 11 shows a schematic of the modified LOCA DBE experimental test facility that includes a superheater in the heat supply system (red line).

The modified LOCA DBE experimental test facility employed a boiler–compressor–superheater to increase the temperature and pressure in the chamber substantially faster than when using the conventional boiler–compressor configuration. This setup was expected to provide more thermal energy to the steam to ensure an initial rapid change in temperature and pressure even considering heat exchange between the steam and the chamber. We expected to obtain an effect similar to that of chamber insulation modeled in the MARS-KS simulation.

4.2. Comparison of the modified experimental test results with the standard profile

In Sections 2 and 3, the LOCA DBE profile for the OPR-1000 (Optimized Power Reactor-1000) NPPs was used. This profile cannot be applied to the later developed APR-1400 (Advanced Power Reactor-1400) NPPs; thus, in the modified LOCA DBE test facility, the standard profile was changed to comply with the requirement of the APR-1400 NPPs. This changed profile encompasses the OPR-1000 profiles employed above.

The modified DBE profile has a maximum temperature of over 230 °C and a maximum pressure of 700 kPa. This creates a harsher environment compared to the standard profiles used in Sections 2 and 3, with substantially higher initial temperature and pressure slopes. In addition, the start time of chemical spraying was changed to 250 s instead of 1000 s. The obtained profile is harsher than the standard profiles tested in Sections 2 and 3; thus, the temperature and pressure in the chamber are more difficult to auto-control than when following the standard profile.

The modified LOCA DBE test facility, with the addition of a

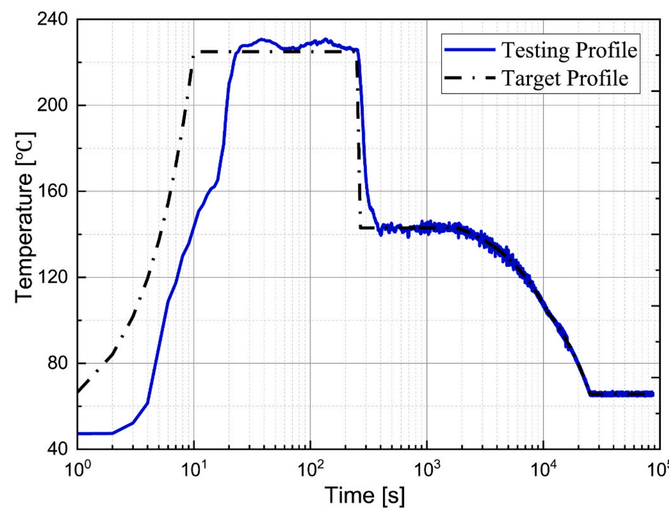

Fig. 12. Test result for the modified LOCA DBE experimental test facility: Temperature.

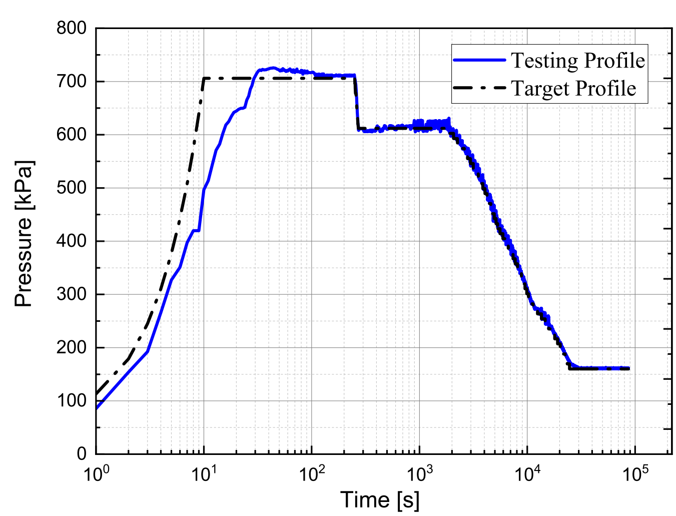

Fig. 13. Test result for the modified LOCA DBE experimental test facility: Pressure.

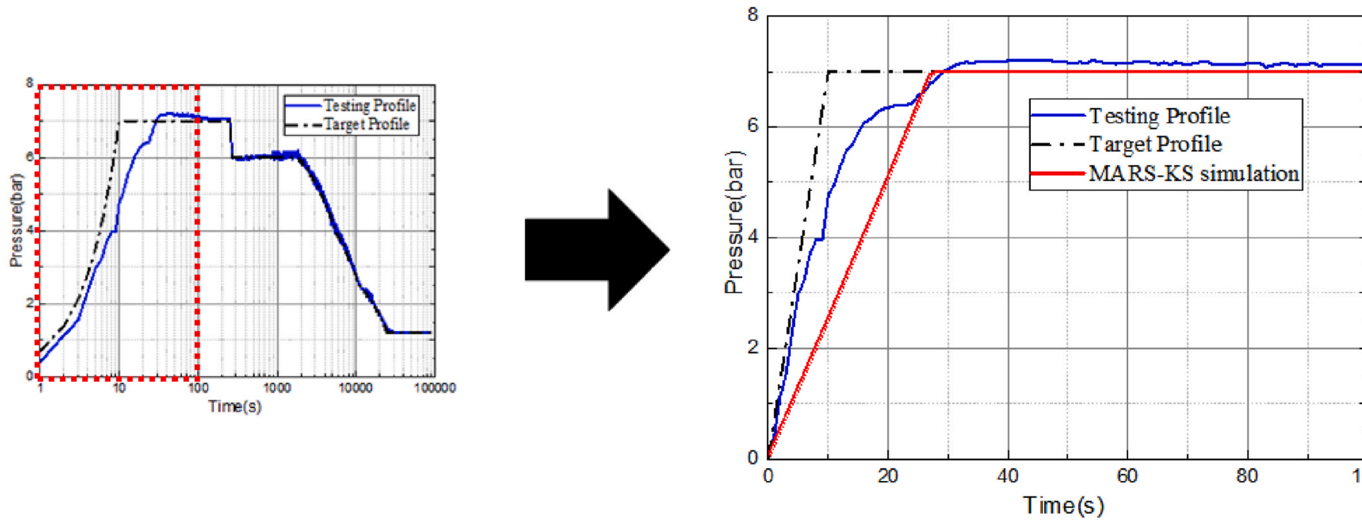

Fig. 14. Pressure profile in the chamber: experimental, target, and simulated using MARS-KS.

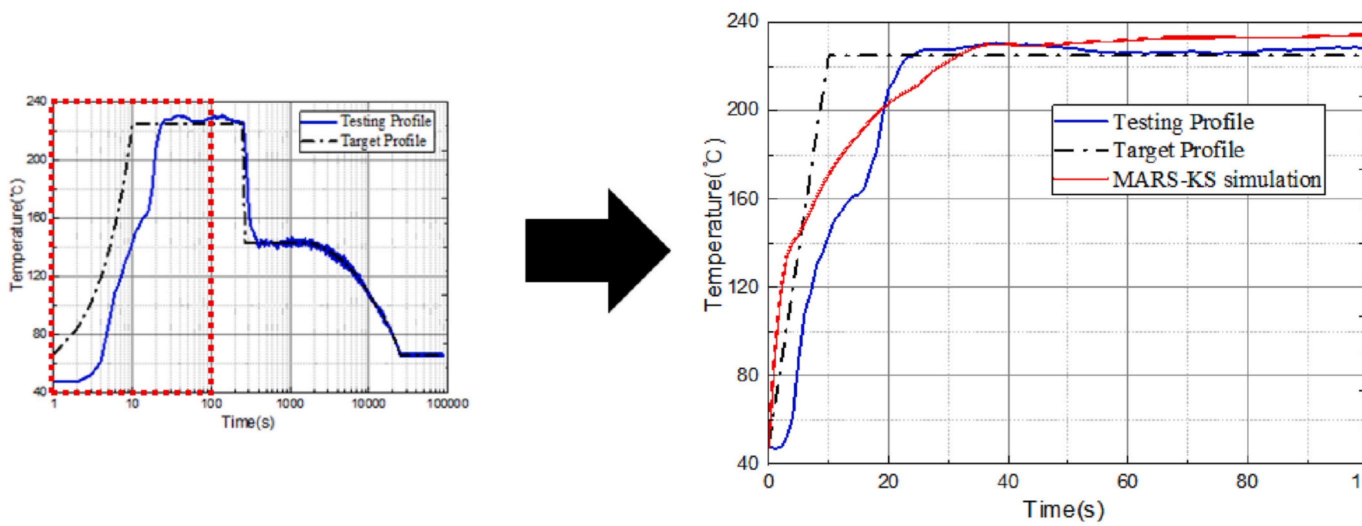

Fig. 15. Temperature profile in the chamber: experimental, target, and simulated using MARS-KS.

superheater, can supply steam at a higher temperature than the original facility, allowing the initial temperature of the steam supplied to the chamber to be approximately 330 °C. The test starts with both the inlet and outlet valves open. The initial supply pressure of the steam was about 15,000 kPa. After it reached the set value of the temperature profile at 50 s, the inlet valve was adjusted to perform proportional control according to the temperature profile. The outlet valve was then set to adjust pressure through proportional control according to the pressure profile plus 20 kPa. The steam supply flow rate was 20000 m^3/h at the beginning of the test; when the proportional temperature control was initiated, the steam flow rate was reduced to 2000–3000 m^3/h. The measured results of the modified LOCA DBE test facility with automatic control and the standard profile are shown in Figs. 12 and 13 below.

As shown in Figs. 12 and 13, the measured temperature and pressure follow the standard profile with an error of about 1–10 s after the initial period of rapid change in the profile. This proves that insufficient thermal energy of the steam supplied to the chamber owing to the heat exchange between the steam and the chamber wall was indeed the reason why the temperature and pressure did not follow the reference profile. At the same time, the addition of a superheater to the heat supply system to provide additional thermal energy to the steam proved to be a viable solution. Thus, new MARS-KS simulations of the modified facility were performed to compare the experimental and simulation results.

4.3. Verification with MARS-KS simulations

MARS-KS simulations were conducted to validate the experimental results for the modified facility. Overall, experimental results for the modified facility agree with the target profile, as depicted in Figs. 12 and 13. The MARS-KS model for the modified facility used the same nodalization as in Fig. 6. Only the boundary conditions were modified to incorporate the use of superheated steam.

Figs. 14 and 15 show the experimental, target, and simulated pressure and temperature profiles in the chamber. Because the primary objective of the tests of the modified facility was to achieve a rapid increase in pressure and temperature at the beginning, the MARS-KS simulation was conducted only for the initial 100 s. In the MARS-KS simulation, the pressure increased to 700 kPa within 26 s, closely matching the experimental profile. However, the initial slope of the experimental profile is steeper than that of the simulated profile. The temperature in the MARS-KS simulation reached 220 °C in 30 s, whereas in the experimental profile, this temperature is reached in 23 s. Therefore, although the MARS-KS results are slightly delayed, the initial slope of the experimental profile is lower than that of the simulated profile.

5. Concluding remarks

Capacity for EQ testing in DBE conditions is a crucial aspect of the safety and operation of NPPs. EQ involves testing and verification of the performance of key safety-related SSCs under various harsh DBE conditions. EQ is essential to ensure that NPPs can operate safely and reliably, even during DBEs.

ROK has been actively developing its nuclear industry, and its ability to secure the capability to test nuclear equipment is crucial for both domestic safety and international competitiveness. The development of advanced testing facilities and methodologies for EQ can give ROK a significant edge in the global nuclear market. The greatest challenge in the construction of EQ facilities arises from the need to rapidly increase both temperature and pressure in the test chamber. Specifically, the temperature and pressure must be increased to 170 °C and 500 kPa, respectively, within 10 s.

In the first phase of experiments, we injected saturated steam at 170 °C and 900 kPa into the chamber. However, this approach did not allow to reach the target temperature and pressure within the target timeframe because of the loss of heat of saturated steam to the heating of the inner walls of the chamber.

We used simulations in MARS-KS to devise a solution. Based on the insights derived from the simulation results, we formulated and verified a new strategy: the introduction of superheated steam at an elevated temperature of 330 °C and a pressure of 15,000 kPa. The modified test facility allowed to reach the target temperature and pressure in the chamber within a substantially shorter timespan, marking a significant advancement in EQ testing capabilities for NPP equipment in ROK.

CRediT authorship contribution statement

Kyungha Ryu: Conceptualization, Supervision, Writing – original draft. **Seonggyu Cho:** Data curation, Writing – original draft. **Taeho Roh:** Data curation. **Sangkyo Kim:** Data curation. **Taekook Park:** Data curation. **Taehyun Lee:** Data curation. **Jongwon Park:** Data curation. **Jaehyun Cho:** Conceptualization, Data curation, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported by the Korean Government Ministry of Trade, Industry, and Energy (20215810100050, 20218801010030, 20223030040060, RS-2024-00430799, RS-2024-00437087). This work was also supported by the Nuclear Safety Research Program through the Regulatory Research Management Agency for SMRS (RMAS) and the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 1500-1501-409).

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