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Original Article

Survivability assessment of Viton in safety-related equipment under simulated severe accident environments

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ABSTRACT

To evaluate equipment survivability of the polymer Viton, used in sealing materials, the effects of its thermal degradation were investigated in severe accident (SA) environment in a nuclear power plant. Viton specimens were prepared and thermally degraded at different SA temperature profiles. Changes in mechanical properties at different temperature profiles in different SA states were investigated. The thermal lag analysis was performed at calculated convective heat transfer conditions to predict the exposure temperature of the polymer inside the safety-related equipment. The polymer that was thermally degraded at postaccident states exhibited the highest change in its mechanical properties, such as tensile strength and elongation.

1. Introduction

According to an International Atomic Energy Agency report [1], the probability of occurrence of a severe accident (SA) in a nuclear power plant (NPP) is remarkably low. Nevertheless, the SAs that occurred at Three Mile Island (TMI) and Fukushima Daiichi resulted in substantial social and economic impacts. To prevent and mitigate the effects of an SA, safety-related equipment such as emergency reactor depressurization valves (ERDVs) are installed in NPPs. It is necessary for the safety-related equipment to execute its expected safety function in an SA environment during the required period to ensure the integrity of the containment building, thereby preventing the release of radioactive materials and mitigating the effects of accident [2]. The equipment survivability (ES) of safety-related equipment during the SA environment has been emphasized [3,4]. Based on the reaction between the fuel cladding materials and the coolant in the SA environment, increased temperature, radiation, and pressure can be generated owing to the burning of combustible gases. Safety-related equipment in NPPs must perform its safety functions during normal operation conditions and design basis events. Therefore, technical qualification methods have been established, such as Institute of Electrical and Electronics Engineers (IEEE) standards 323 and 344 [5–7]. However, at present, there are no international standards or regulations about technical qualification methods to assess the survivability of equipment for conditions beyond design basis events, including SA [8]. Moreover, owing to a lack of equipment that can simulate SA environments, ES assessment has not yet been conducted in accordance to specific test types. Therefore, it is not feasible to assess ES for equipment that is planned to be installed in newly constructed NPPs [9].

There are several steps of ES assessment, as illustrated in Fig. 1. The first step defines the safety functions according to the regulations, such as the safety reactor shutdown, mitigation of accident effects, and maintenance of containment integrity. Subsequently, the systems and equipment destined to perform the defined safety functions are selected, and the exposure environments of these systems and equipment are determined. The qualification for such equipment can be achieved by comparing the equipment qualification (EQ) data, experimental results, and degradation temperature of the materials comprising the equipment in an SA environment in an NPP. In the cases in which the assessment

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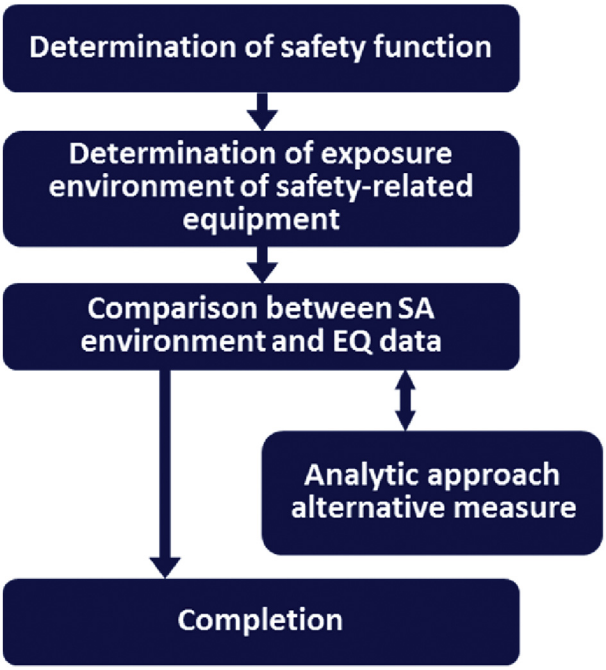

Fig. 1. Assessment procedure of equipment survivability [3].
EQ, equipment qualification; SA, severe accident.

method was based on experimental results, the ES was assessed by performing experiments in the SA environment. In some cases, it is feasible to derive the mitigated environment through thermal lag analysis or alternative measures, such as fire wrap and relocation [10–12]. Some of the equipment that uses polymer components, such as Viton, is likely to fail owing to degradation. In general, polymer materials have been reported to be more easily degraded than metals at high temperatures and pressures and in a radiation environment [13,14]. Therefore, ES assessment of the polymer is important to ensure the safety functions of the safety-related equipment.

In this study, a thermal degradation test was performed to evaluate the degradation effect of the polymer Viton for the temperature profile of SA environments. An electric furnace was used to provide the temperature profile of the SA. To simulate the rapidly elevated temperature in the initial state, a specimen-shifting system was designed using the temperature gradient of the electric furnace. Furthermore, the mechanical properties of the polymer after each SA temperature profile state were obtained using tensile tests.

In this study, a performance test was conducted to verify the simulation environment of the SA for the ES assessment. The performance test was conducted by measuring the temperature distribution of the equipment. Furthermore, tests were performed to evaluate the degradation effect of the temperature profiles at each SA state. In addition, the exposure temperatures of the polymer components inside the equipment during the SA temperature profile were analyzed using thermal lag analysis.

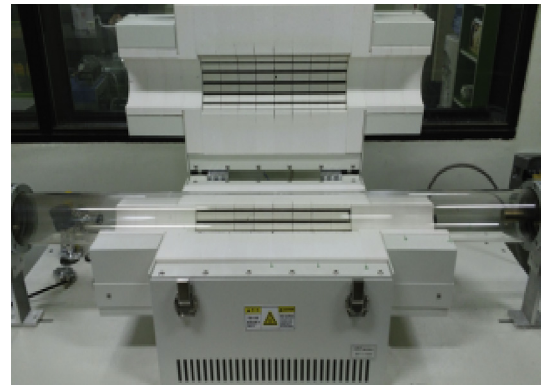

Fig. 3. Photograph of the test equipment using the electric furnace.

2. Materials and methods

2.1. Test equipment

The test equipment consisted of an electric furnace with a specimen-shifting system. Figs. 2 and 3 show typical test equipment. The rapidly heated and cooled regions were simulated by using the shifting system to control the location of the specimen. The shifting system was used to establish the temperature gradient in the tube. Specimen consisted of Viton and a metal housing made of carbon steel for uniform heat transfer to the polymer, as shown in Fig. 4. The dimensions of the metal housing were 25 mm diameter and 110 mm length. The dimensions of the Viton specimen were 5 mm diameter and 80 mm length.

2.2. Test procedure and conditions

For the ES assessment of safety-related equipment, it is important to accurately simulate the SA environment. However, the construction of equipment that can simulate the SA environment is technically challenging because of the unique phenomena associated with SA, such as hydrogen burns. Therefore, ES was assessed by individually evaluating the effects of each environmental factor associated with SAs on the degradation of materials. Based on the actual SA environment, such as the case of hydrogen burns, the elicited temperatures increase rapidly with temporal progression of the accident. This effect varies in accordance with

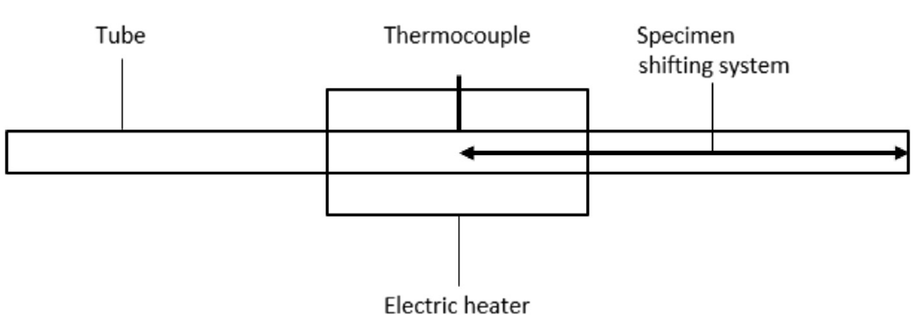

Fig. 2. Schematic illustration of the test equipment.

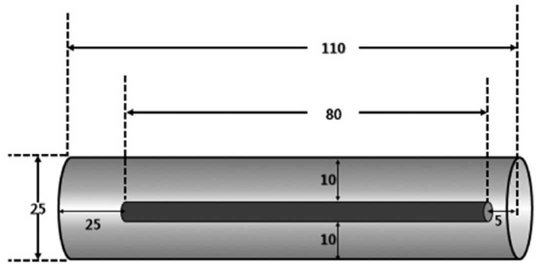

Fig. 4. Schematic diagram illustrating the degradation of the test specimen (mm).

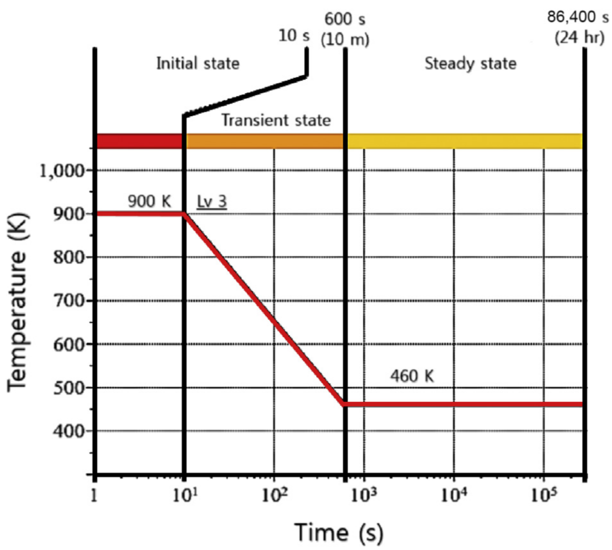

Fig. 5. Temperature profile of SA conditions for the assessment of ES [3]. EQ, equipment qualification; SA, severe accident.

the particular accident scenario. However, from a conservative point of view, it is necessary that the SA environment used for the ES assessment be able to account for all accident scenarios. Therefore, it is important that the temperature range used to evaluate the ES be divided into several intervals according to the accident scenario and that a single profile be constructed by applying the stored histogram method. The temperature profiles of the SA environment for the ES assessment were constructed based on these processes, as illustrated in Fig. 5. These temperature profiles can be divided into initial, transient, and steady states. In the initial state, the temperature increases owing to hydrogen burn from an initial temperature of 300–900 K; it is then maintained at 900 K for approximately 10 s. The transient state occurs within the time period from 10 to 600 s after the onset of the accident. Because at that instant the hydrogen burns ceases, the temperature decreases to 460 K. Finally, in the postaccident state, a steady state is maintained at 460 K owing to the decreased heat of radioactive materials released into the containment through the damaged core.

First, the assessment of the equipment was conducted. For the performance test, the temperature distribution of the furnace was evaluated by measuring the temperature at 5-cm intervals from the center of the equipment. The measured temperature distribution of the tube is shown in Fig. 6. In addition, Fig. 7 shows the results obtained from the performance test of the equipment. Degradation tests were conducted using this developed test equipment with a specimen of the polymer Viton.

2.3. Analysis method

During an SA, the temperature of the atmosphere in the containment increases. However, the surface of the equipment is exposed to a relatively low temperature because of the loss incurred during the heat transfer process in the atmosphere. Therefore, to evaluate the ES, the exposure temperature of the equipment needs to be predicted. It is possible to predict the exposure temperature of the equipment through thermal lag analysis of the atmosphere in the containment, based on heat transfer theory.

In this study, an analysis model was designed for the thermal lag analysis, as illustrated in Fig. 8. The variable V is the velocity of the particles in the atmosphere in the containment induced by the hydrogen burn during the SA. The variables D and L, respectively, represent the model's diameter and length. Correspondingly, C_P is the specific heat of the carbon steel of the housing material. The

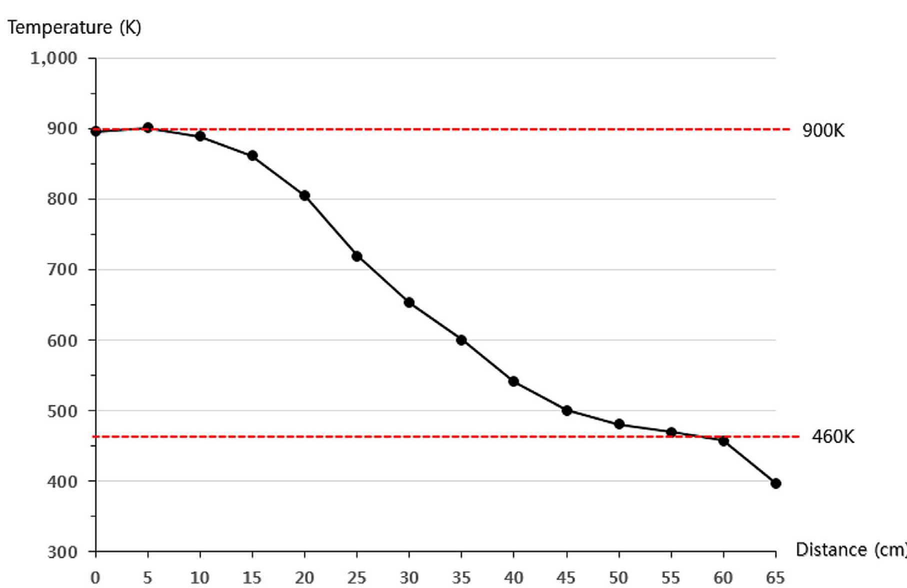

Fig. 6. Measured temperature distribution of the equipment [15].

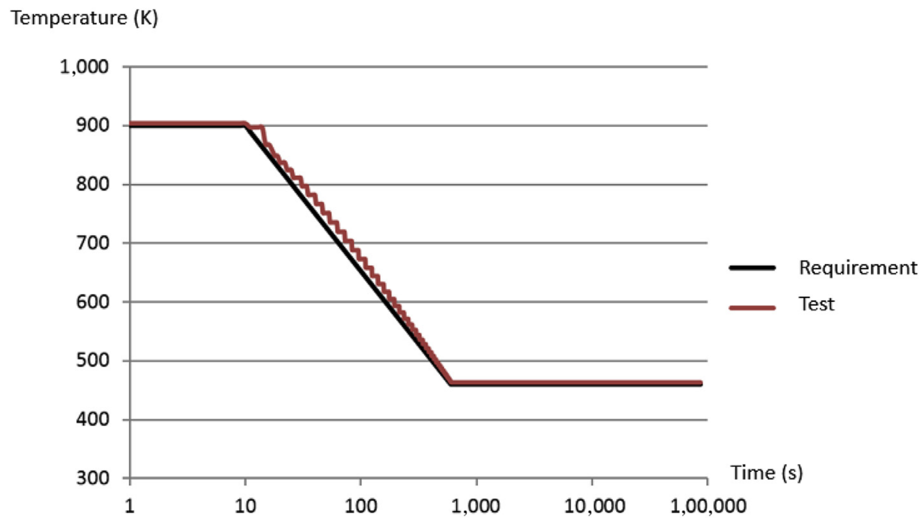

Fig. 7. Performance test results [15].

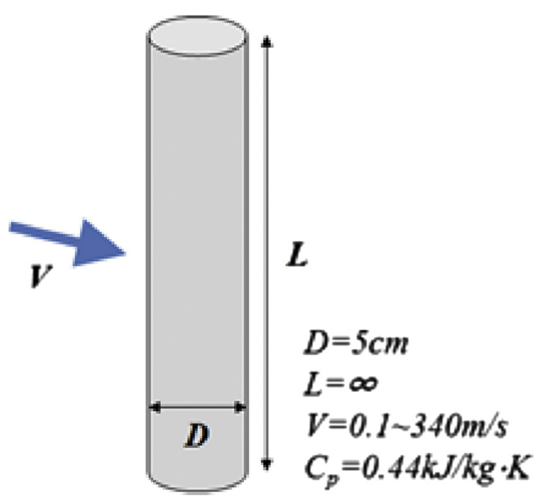

Fig. 8. Analysis model used for the assessment of ES [15].
ES, equipment survivability.

thermal properties of the metal housing and Viton used in this analysis are presented in Table 1 [16]. In an SA environment, the hydrogen generated and accumulated in the containment because of the reaction of the cladding materials and coolant at high temperatures caused hydrogen burn and was rapidly expelled to the atmosphere. This phenomenon also changed the velocity of the atmospheric air and the convective heat transfer coefficient. Therefore, this phenomenon was applied to the analysis model to analyze the temperature in the environment of the hydrogen burn. Moreover, for the analysis, the following assumptions were made: (1) a steady state condition, (2) air was considered an ideal gas, (3) radiation effects were negligible as the resistance to heat transfer by conduction and radiation were lower than that by convection, and (4) the surface temperature was uniform [17].

Table 1
Thermal properties of air, carbon steel, and Viton [16].

Properties	Air	Carbon steel	Viton
Density (kg/m^3)	1.18	7860	1100
Specific heat (J/kg·K)	1003.62	473.0	1660
Thermal conductivity (W/m·K)	0.03	48.9	0.25

The heat flux for forced convection can be calculated by Newton's law in accordance with Eq. (1), and the heat transfer coefficient can be calculated using the Nusselt number. Generally, flows through a cylinder and a sphere cause flow separation, which is difficult to analyze. Therefore, this flow has been studied experimentally or numerically, and numerous empirical relation equations for heat transfer coefficients have been developed. The convective heat transfer coefficient was calculated using the equation proposed by Churchill and Bernstein, who introduced it in 1977; this equation is valid for RePr > 0.2 [18].

$$\dot{Q} = h(T_S - T_\infty) \tag{1}$$

$$Nu = \frac{hD}{k} = 0.3 + \frac{0.62Re^{\frac{1}{2}}Pr^{\frac{1}{3}}}{\left[1+\frac{0.4}{Pr^{\frac{2}{3}}}\right]^{\frac{1}{4}}}\left[1+\frac{Re^{\frac{5}{8}}}{28200}\right]^{\frac{4}{5}} \tag{2}$$

where h, Re, and k are the convective heat transfer coefficient, Reynold's number, and thermal conductivity, respectively. Using the analyzed convective heat transfer coefficients, computational analysis was performed on a 3-D model of the ERDV actuator to predict the exposure temperature of the equipment.

3. Results and discussion

3.1. Degradation test

The performance test of the equipment for the assessment of ES using the tube furnace was based on an SA temperature profile simulation. The temperature was measured at 5-cm intervals from the center of the furnace. Within the region extending up to 10 cm from the center of the equipment, a temperature of 900 K was maintained. As the distance from the center increased, the temperature decreased. The temperature at 60 cm from the center was 460 K. The test results demonstrate that, using the developed equipment, the temperature profile with a 900 K peak can be simulated for ES assessment of ERDV. The initial state was simulated within the spatial range of 10 cm from the center of the equipment. The transient state can then be simulated by shifting the specimen from 10 to 60 cm from the center of the equipment.

A degradation test was performed to evaluate the degradation effect during each state of the SA temperature profile within air. The

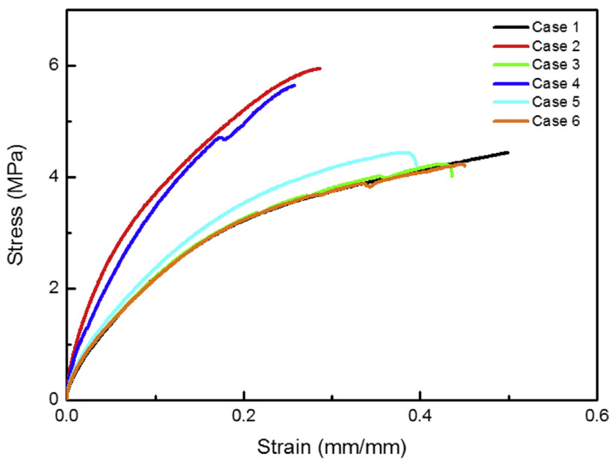

Fig. 9. Stress–strain curves of degraded specimens (Viton) [15].

test was performed for four cases, and the mechanical properties of Viton exposed to each state were measured using the tensile test, as illustrated in Table 2 and Fig. 9.

These tests revealed that the yield stress and Young's modulus of the specimens were similar to those of the reference specimen. The Young's modulus and yield stress of the specimen in case 3 were 18.93 and 3.45 MPa, respectively. However, as revealed by cases 2 and 4, the specimen that was exposed to the full conditions of the SA environment at a steady state exhibited failure at a lower value of strain than the reference. It is conjectured that, compared with the initial state, the high-temperature environment after the accident significantly affected the degradation of Viton. The condition associated with case 1 is a nondegraded condition, whereas case 2 represents a full SA condition that includes all the temperature profiles from the onset of the accident to 24 h. Test conditions of the initial and transient states (~10 m) and of the postaccident state (10 m at ~ 24 h) were included in cases 3 and 4. The tests in cases 5 and 6 were associated with exposed relative humidity (RH) values of 0 % and 40 % at 360 K, respectively, and were performed to evaluate the effects of RH on the degradation of Viton. These tests revealed a negligible variation in the Young's modulus and yield stress between the specimens for cases 5, 6, and the reference. These results demonstrate that RH may have negligible effects on the degradation of Viton.

Table 2
Degradation test results.

Cases	Young's modulus (MPa)	Yield stress (MPa)
1. Reference	20.50	3.29
2. Full conditions	40.82	4.75
3. Initial and transient states	18.93	3.45
4. Postaccident state	40.20	4.60
5. RH 0 %, 360 K	22.69	3.60
6. RH 40%, 360 K	21.19	3.25

In general, when a polymer is exposed to heat, free radicals form within the molecular structure, and these radicals form new bonds within or at the end of the molecule. This phenomenon was accompanied by cross-linking, and scission of bonds caused increases and decreases in the molecular weight. One of these effects was dominant depending on the molecular structure and environment [19]. In the case of Viton, cross-linking occurred primarily because of heat. Free radicals were generated by the scission of the bonds inside the molecular structure, and cross-linking between monomers occurred. Furthermore, with this change of the molecular structure, hardening occurred in which the Young's modulus and yield stress increased. Correspondingly, these changes of the mechanical properties caused degradation in the hardening and sealing performance of the valve. Furthermore, C=O bonds are generated by the reaction between the free radicals generated from the scission reaction and oxygen in atmospheric air. These bonds are also known to cause hardening of the polymer [20].

In cases 2 and 4, Viton hardened owing to its cross-linking and oxidative degradation, which formed C=O bonds after a relatively long heat exposure period. However, in case 3, owing to the short heat exposure time, the mechanical properties were almost unchanged.

However, because there are various environmental factors, such as radiation and heat, tests under these environmental factors required further understanding of the degradation behavior of Viton in the SA environment. In addition, the specific failure criteria for Viton seals in SA conditions have not been well established. According to the previous study conducted by the Korea Atomic

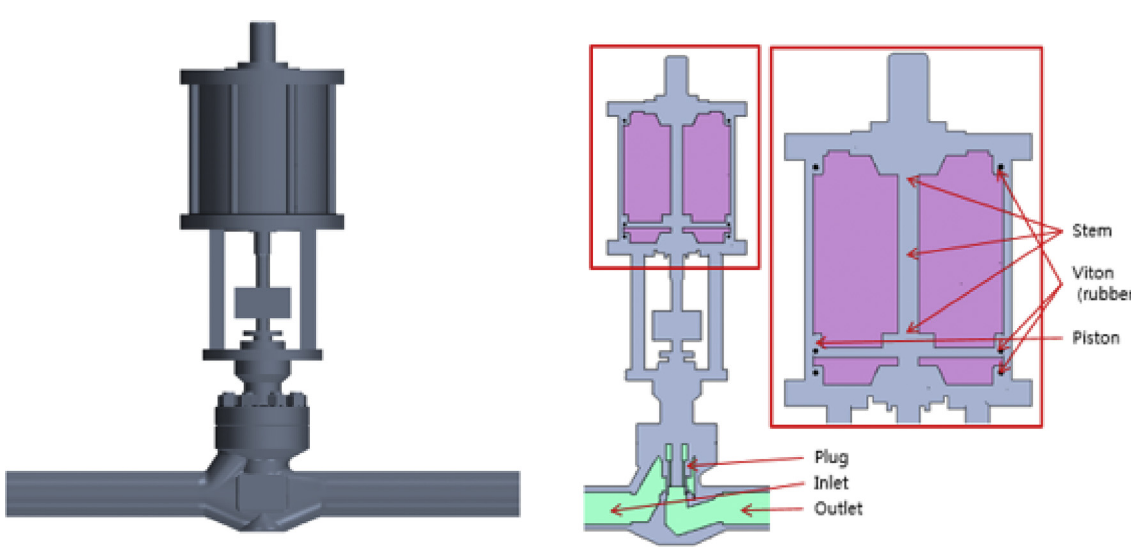

Fig. 10. ERDV geometry used for thermal lag analysis [15].
ERDV, emergency reactor depressurization valve.

Energy Research Institute on the effect of thermal degradation on nonmetallic materials, such as cable materials, the integrity of materials in NPPs was considered to be maintained until the materials degraded to 50% of their initial elongation at break [19]. However, it is unreasonable to assess ES by applying these criteria to all nonmetallic materials in NPPs. Therefore, further detailed research will be required to establish the failure criteria of Viton in thermally exposed environments.

3.2. Thermal lag analysis

In the SA environment, the velocity of the atmosphere in the containment is equal to the speed of sound owing to the hydrogen burn. In this situation, forced convective heat transfer was dominant. Therefore, the convective heat transfer was calculated using the Churchill and Bernstein correlation in accordance with Eq. (2) [18]. To predict the exposure temperature of the polymer inside the ERDV, 3-D modeling was performed, as illustrated in Fig. 10, and thermal lag analysis was performed by computational analysis.

Because the hydrogen burn was assumed to occur only at the initial state, for a conservative assessment, convective heat transfer coefficients were calculated by taking into account the burning status of hydrogen used in the initial and transient states. Correspondingly, a convective heat transfer coefficient of 703 $W/m^2 \cdot K$ was used for the initial and transient states. Moreover, a value of 30 $W/m^2 \cdot K$ was used for the postaccident state.

The exposure temperatures of each component in ERDV, as predicted by the computational analysis, are presented in Figs. 11 and 12. The temperature of the specimen increased to approximately 310 K and 616 K during the initial and transient states, respectively. The rapid temperature increases during the initial and transient states were due to the rapid heat transfer from the atmosphere to the ERDV because of the increased velocities of the atmospheric particles. However, during steady state and after 600 s from the initiation of the accident, the temperature of the ERDV gradually converged to the temperature of the atmosphere owing to the low heat transfer rate.

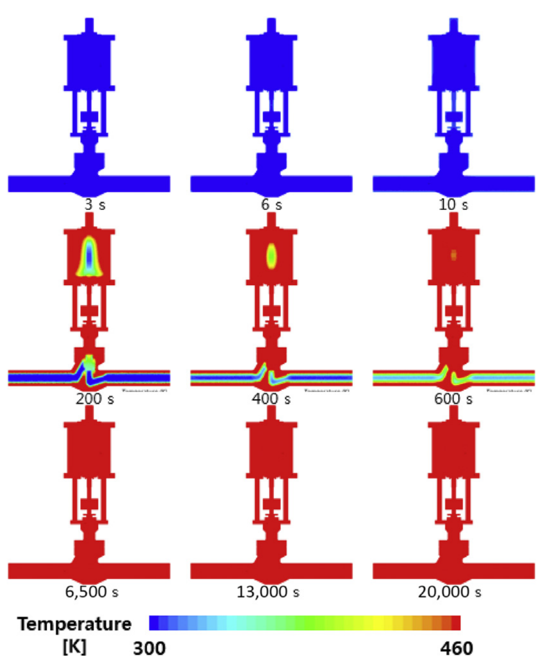

Fig. 11. Temperature distribution analysis of ERDV in SA conditions [15].
ERDV, emergency reactor depressurization valve; SA, severe accident.

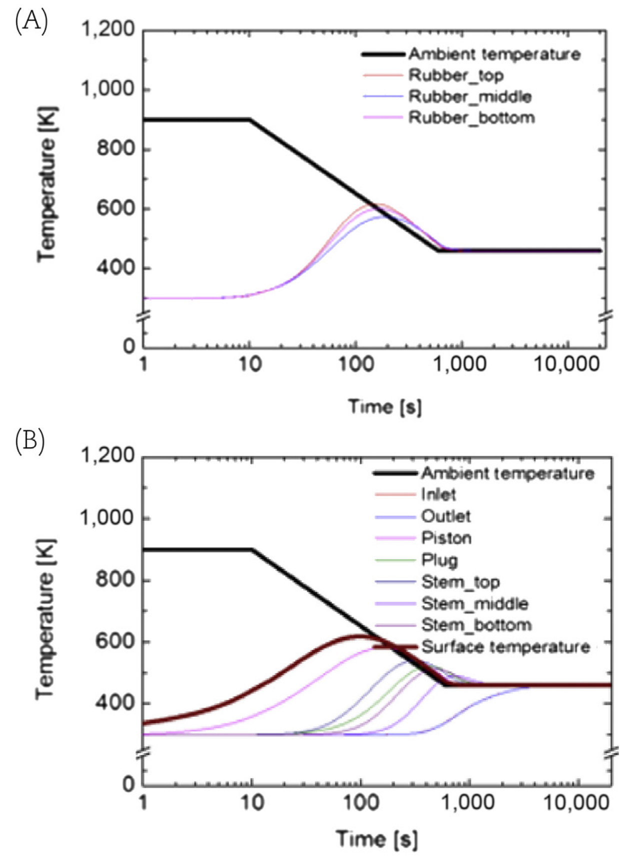

Fig. 12. Thermal lag analysis results of ERDV components in SA conditions. (A) Exposure temperature profiles of Viton seals. (B) Exposure temperature profiles of other parts [15].
ERDV, emergency reactor depressurization valve; SA, severe accident.

4. Conclusion

In this study, performance and degradation tests were conducted to evaluate degradation effects of a polymer. Moreover, thermal lag analysis was performed to predict the temperature of the polymer in an SA environment. A performance test was conducted via measurement of the temperature distribution in the equipment.

For the thermal lag analysis, the convective heat transfer coefficient was calculated during the burning of hydrogen. Moreover, using the calculated coefficient, thermal lag analysis using a 3-D model of the ERDV actuator was conducted through computational analyses. The analysis results revealed that Viton was exposed to temperatures up to 610 K.

Tests were conducted to evaluate the degradation effect during each state of the temperature profile of the SA. As part of this test, the specimens were exposed to different SA temperature profiles. Moreover, the mechanical properties of the polymer specimen were measured by tensile tests. According to the results, the initial and transient states were found not to significantly affect the mechanical properties of Viton. However, the specimen exposed to the postaccident state failed at a lower strain than the specimen exposed to the initial state. The specimens exposed to the full SA environment were degraded to the highest extent.

Conflict of interest

There is no conflict of interest.

Acknowledgments

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