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INVESTIGATION OF AIR OPERATED VALVE PERFORMANCE BY ACCELERATED LIFE TEST

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ABSTRACT

In nuclear power plants, many valves are operated under harsh conditions such as high temperature-high pressure and radiation environments but high levels of reliability are required from valves for safety operation of the power plant. However, deterioration of valve parts due to power plant aging and the system's transient phenomena due to rapid load shift operation are acting as obstacles that impede securing valve reliability.

To secure valve reliability, quality in design/production stages and intended performance under the worst operation conditions shall be assured. Also, it is necessary to meet the reliability level given in the specified environment conditions and to perform the designed functions throughout its lifetime without failure.

Meanwhile, to enhance the safety and the operation of nuclear power plants, it is important to early detect the deterioration of valve performance and take measures quickly. However the mechanical defects of valves are occurs suddenly in various types and it is very difficult to predict them.

Valves which are responsible for the important functions of nuclear power plants are confirmed performance and durability before the installation. However, the performance degradation and defects of the valve are occurs during plant operating. Therefore, to ensure that the valves perform their designed functions for the requested period without failure, it is important to demonstrate their reliability in all stages such as design, production, and operation.

The purpose of this paper is the best preventive maintenance and life cycle management, including comprehensive quality control measures established in the valves. Therefore, the performance verification through performance validation tests were performed on air operated valves most commonly used in nuclear power plants. In addition, the leakage and stroke time were measured by performing an accelerated life test (thermal aging, radiation exposure, mechanical cycling) under the operating conditions of the power plants.

Results show that the thermal aging of valves has significant effects on the valve seat and stem leakage but it has almost no effect on the actuator leakage and the stroke time. Meanwhile, it is found that the radiation and mechanical aging of valves have no clear effect on the leakage and stroke time of valves.

KEYWORDS: Accelerated Life Test, Thermal Aging, Radiation Exposure, Mechanical Cycling, Air Operated Valve, Plant Design Life Time, Nuclear Power Plant

INTRODUCTION

In nuclear power plants, many valves are operated under harsh conditions such as high temperature-high pressure and radiation environments but high levels of reliability are required from valves for safety operation of the power plant. However, deterioration of valve parts due to power plant aging and the system's transient phenomena due to rapid load shift operation are acting as obstacles that impede securing valve reliability. To secure valve reliability, quality in design/production stages and intended performance under the worst operation conditions shall be assured. Also, it is necessary to meet the reliability level given in the specified environment conditions and to perform the designed functions throughout its lifetime without failure. Currently, the experimental/analytical study on the flow rate[1)], performance evaluations of actuators[2)] and valve leakage evaluations[3)] were carried out, and has a significantly contribute to an improvement in the valve quality. The purpose of this paper is the best preventive maintenance and life cycle management, including comprehensive quality control measures established in the valves. Therefore, the performance verification through performance validation tests were performed on air operated valves most commonly used in nuclear power plants. In addition, the leakage and stroke time were measured by performing an accelerated life test (thermal aging, radiation exposure, mechanical cycling) under the operating conditions of the power plants.

TEST SPECIMEN AND METHODS

Test Valve

Safety related Q class valves are installed 200 at one unit of nuclear power plants. Test valve is a Q class 2 inch air operated valve which was installed reactor coolant piping system of nuclear power plants. Table 1 and Figure 1 show the specification of the valve being used in this study and its pictures. The valve is a globe-type, 2 inch on/off air operated valve that is most frequently used in nuclear power plants and its design flow rate and pressure are 2,050 psi and 200 gpm respectively. Acceptance stroke time is within 10 seconds and seat leakage acceptance rate is within 1.0 cc/min.

Table 1. Specifications of test valve

Title	2 inch Air Operated Valve
Type	Globe
Design Pressure	2050 psig (144 kgf/cm^2)
Design Temp	350 ℉ (177 ℃)
Design Flow Rate	200 gpm (0.76 m^3/min)
Operation Pressure	1000 psig
Open-Close Time	10.0 sec
Seismic	5g
Acceptance Leakage	< 1.0 cc/min
Material	Body/Trim : ASTM A182
Air Supply Pressure	4 bar
Fluid	H_2O
Valve Weight	140 lb

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Fig. 1. Test valve

Table 2 shows the environmental conditions of the test valve in the nuclear power plant. The test valve is used for 40 years under 50℃ environmental conditions and exposed to 4.0×10^5Gy radiation to perform 2,000 instances of On/Off operation.
In this paper, in order to understand the influence of the aging environment on valve performance, accelerated test were carried out. Accelerated testing of the valve is applied by calculating the acceleration based on the environment temperature and the radiation dose in the installation environment of valve.

Table 2. Environmental conditions of test valve

Life Time	Temp.	Radiation	Cycle
40Yr	50℃	4.0×10^5Gy	2,000

Basic Performance Test
Valves related to the safety of nuclear power plants shall be confirmed that they do not pose any problem with design, production and performance through testing that satisfies KEPIC[4)](or ASME[5)]) technical criteria.
In this paper, representative tests indicated in Table 3 among the said KEPIC's technical criteria are conducted to verify the test valve's basic performance.

ISSN: 2277-9655
Impact Factor: 4.116

Table 3. Functional test item of valves

Test Item	Test Content
Pretest Inspection	This is to establish criteria to verify the compliance and functions of the test valve's parts. The actuator is driven by minimum power to conduct the valve seat, stem leakage test and measure stroke time.
End Loading Test	The objective of this test is to demonstrate operability when a pipe on which the valve is installed becomes broken for any reason. The leakage test is conducted and the stroke time is measured while the end load is applied to the valve.
Seismic Test	This is to check whether the valve is operated without any problems even when after an earthquake has taken place. The valve's opening and closing capability is checked while a load simulating that of an earthquake is applied.
Post Test Inspection	This is to check whether there is any damage, defect or deformation in the valve. The actuator is driven by minimum power to conduct the valve seat, stem leakage test and measure stroke time.

Accelerated Thermal Aging Test

Valves installed in nuclear power plants are exposed to high temperatures according to their installation environment and because of this, valve components experience changes in physical properties. To reproduce this thermal aging within a short period of time, various accelerated aging test methods have been suggested and used. In this paper, thermal aging is reproduced according to the temperature conditions of power plants by using accelerated thermal aging conditions calculated with Arrhenius equation in Equation (1).

$$t_2 = t_1 \times \exp\left\{\frac{E_a}{k}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right\} \qquad (1)$$

Where t_1 is actual aging time, t_2 is accelerated thermal aging time, T_1 is environment temperature, T_2 is accelerated thermal aging temperature, E_a is activation energy and k is Boltzmann constant.

The activation energy means the minimum energy needed for the substance's chemical reaction and if that value is negligible, the accelerated thermal aging time drawn from the Arrhenius equation will increase.

The substance's activation energy in Equation (1) is obtained with Equation (2) according to ASTM E1641-99[6)].

ISSN: 2277-9655
Impact Factor: 4.116

$$E_a = -\frac{R}{b}\left\{\frac{d\log\beta}{d\left(^1/_T\right)}\right\} \qquad (2)$$

Where E_a is activation energy, R is gas constant, b is constant, T is temperature when specific mass decreases and b is heating speed.

Non-metallic materials that form valves have different activation energy values from each other. As it is impossible to conduct accelerated thermal aging tests with these various activation energy values, it is necessary to select one representative value. In this paper, the smallest value among the activation energy values of substances that form each device is used in determining the accelerated thermal aging test conditions to get a conservative result (See Table 4).

If this test sample is exposed to temperatures of 50℃ for 5 years, it corresponds to the exposure to the temperatures of 135℃ for 12 hours. The thermal aging test was conducted under this condition.

Figure 2 shows the test valve's thermal aging test chamber and Table 5 presents accelerated thermal aging test conditions.

Table 4. Activation energy of non-metallic materials

Material	Graphite	Viton
Use	Bonnet & Cage Gasket, Packing	O-ring, Sealing
Activation energy	1.68 ~ 2.14 eV	1.09 eV

Table 5. Thermal aging test condition

Test No.	Aging Temp [℃]	Test Time [min]	Aging Time [year]	Cumulative Aging Time [year]
1	135.5	667.4	4.77	4.77
2	136.2	700.3	5.21	9.98
3	134.5	686.5	4.49	14.47
4	136.2	741.4	5.48	19.95
5	134.3	486.8	4.39	24.34
6	135.6	741.4	5.26	29.60
7	135.3	800.8	6.23	35.83
8	135.7	615.7	4.42	40.24
9	134.5	677.8	4.50	44.74
10	135.4	761.8	4.33	50.07
11	135.1	1485.7	10.08	60.15
12	135.3	1452.5	9.98	70.13

Fig. 2. Thermal aging chamber and test valve

Accelerated Radiation Aging

Equipment installed in nuclear power plants constantly absorb radiation and accordingly, the molecular structure of parts made of high molecular substances becomes changed due to radiation energy.

Accumulation of these deformations triggers changes in the physical properties of the substances and it results in effects on the operability of equipment.

The amount of energy radiation that transmits to a substance can be quantitatively calculated into irradiation dose. As the aging of non-metallic materials due to radiation is caused by the energy radiation that transmits to substances, test conditions for radiation aging are calculated through the irradiation dose and cumulative irradiation time of radiation applied to substances.

In this paper, the accelerated radiation aging test is conducted for a cumulative radiation amount of 1.66×10^6Gy higher than a cumulative radiation amount of 4.0×10^5Gy for the 40-year operation period of nuclear power plants. The accelerated radiation aging test shall be repeatedly conducted for a total of 9 times and the maximum radiation aging degree is approximately 160 years (See Table 6).

Table 6. Radiation aging test condition

Test No.	Radiation [kGy/hr]	Test Time [min]	Aging Time [year]	Cumulative Aging Time[year]
1	6.16	462	11.39	11.39
2	5.75	433	10.00	21.39
3	5.86	432	10.54	31.93
4	5.72	1608	38.32	70.25
5	5.65	426	14.88	85.13
6	6.22	456	7.38	92.51
7	5.52	1025	23.34	115.85
8	5.82	1598	38.89	154.74
9	6.32	454	11.60	166.34

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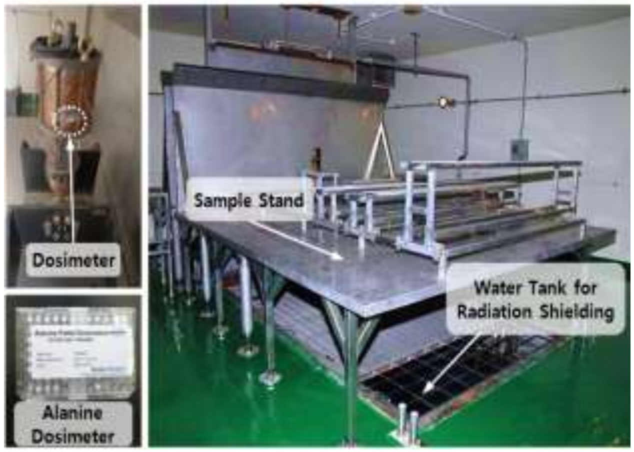

Fig. 3. Radiation exposure of test valve

Accelerated Mechanical Aging

Friction, collision and repetitive stress which occur when equipment is operating may cause abrasion, shape change or fracture of parts. As for valves, since they only conduct repetitive action with one axis as the baseline, the possibility of mechanical aging is limited. However, O-rings, packing and valve plugs which are attached to the operating part are made of non-metallic materials and damage of these parts not only affect the operability but also cause leakage of fluid.

Although metal parts are more resistant against mechanical aging than non-metal parts, if they are used for repetitive operation, their physical properties may become changed.

Mechanical aging by repetitive operation may shorten the operation cycle and it may become accelerated. Although activity repeated in a short term may cause frictional heat, if it does not significantly affect the operational environment of the valve, it may induce an aging effect in the same way as the operation being repeated by a long cycle.

In this paper, it is assumed that the valve is opened and closed by a total of 2,000 instances over a 40-year period of operations. The repetition test was conducted up to 5,000 times in 1,000-time intervals. Currently, the time of one cycle from opening to closing is set at 30 seconds (See Table 7).

Table 7. Mechanical cycling aging test condition

Test No.	Number of Cycle	Test Time [min]	Aging Time [year]	Cumulative Aging Time [year]
1	1000	780	20.0	20.0
2	1000	500	20.0	40.0
3	1000	500	20.0	60.0
4	1000	500	20.0	80.0
5	1000	500	20.0	100.0

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Impact Factor: 4.116

Fig. 4. Mechanical cycling of test valve

RESULTS AND DISCUSSION

Basic Performance

Figure 5, 6 shows the stroke time measurement results among the basic performance tests in Table 2. It shows that the time from opening to closing for 3 valves is 8 sec. - 9 sec. (Fig. 5). Meanwhile, the time from closing to opening is about 5 sec. - 7 sec. (Fig. 6). Therefore, it shows that the stroke time of the test valve meets 10 sec., which meets the criteria for design.

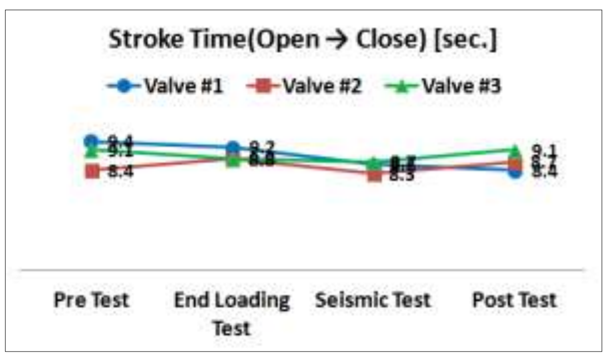

Fig. 5. Valve stroke time (Open → Close)

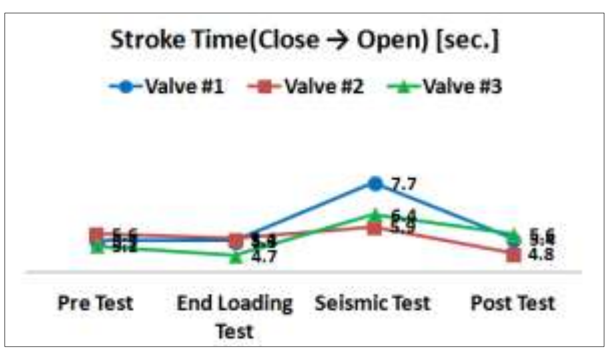

Fig. 6. Valve stroke time (Close → Open)

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Impact Factor: 4.116

Meanwhile, the seat leakage test (Fig. 7) shows that the leakage amount upsurge from the end loading test and post test of valve No.3, and that it exceeded the allowed leakage amount of 1.0 cc/min. It was determined that an excessive load (load exceeding test setting value) was temporarily applied during the end loading test and it damaged the valve components.

In the comprehensive determination based on the basic test results above, it was confirmed that valves No.1 and No.2 are designed/manufactured to meet the design specifications and they are functioning well. Therefore, instead of No.3 valve, No.1 and No.2 valves were used for the aging test thereafter.

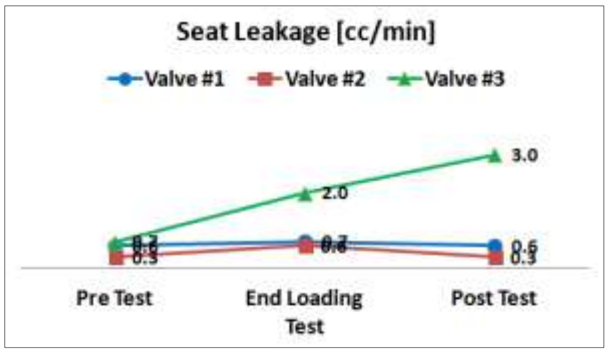

Fig. 7. Valve seat leakage

Accelerated Thermal Aging

Figure 8 shows the results of the valve actuator leakage test. The horizontal axis is the cumulative years of aging (number of operating years) and the vertical axis is the leakage pressure (bar). From the figure, it was found that the leakage pressure of the actuator (leakage amount) increases as the number of operating years increases.

However, leakage pressure is only about 0.25 [bar] at the maximum. It is less than 0.4 [bar] (allowed criteria of leakage pressure for the actuator, it is within 10% of actuator design pressure 4 [bar]). Therefore, we could find that the effect of thermal aging on the valve actuator leakage is not significant.

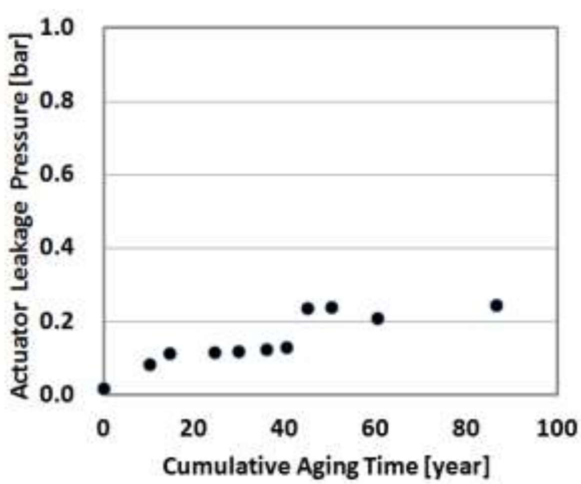

Fig. 8. Actuator leakage

Figure 9 and Figure 10 show the stroke time measurement results of the valve. The horizontal axis is the number of cumulative years for valve aging (number of operating years), and the vertical axis is the stroke distance [mm] per

unit time [sec]. The greater the value is, the faster the stroke time is. As shown in the figure, it is found that the valve is faster when Close → Open (Fig. 10), compared to Open → Close (Fig. 9).
Meanwhile, there is no significant change of the stroke time according to the increase of the operating years.

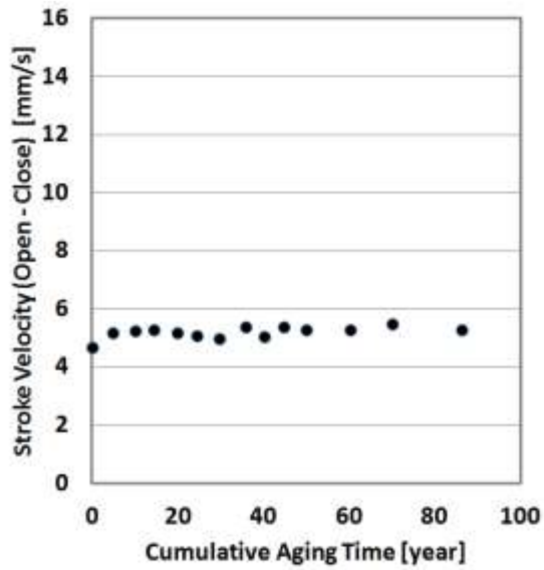

Fig. 9. Valve stroke time (Open → Close)

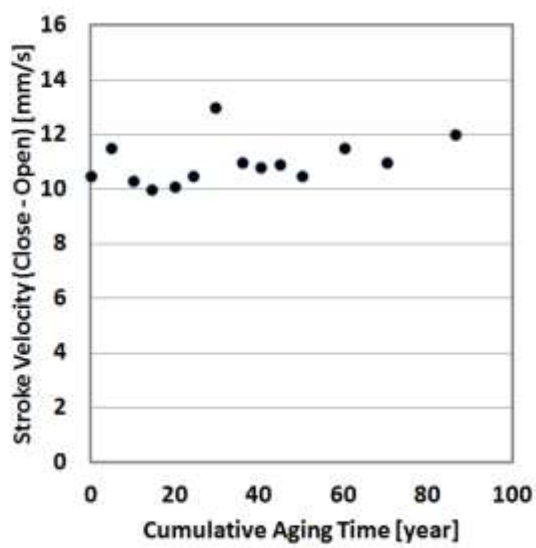

Fig. 10. Valve stroke time (Close → Open)

Figure 11 shows the valve seat leakage test results. The horizontal axis is the cumulative years for valve aging (number of operating years), and the vertical axis is the leakage amount (ml/min). As shown in the figure, it is found that the leakage amount of seat increases according to the increase of the valve operating years. In particular, after 30 years of operation, the leakage amount is rapidly increased, and it exceeds 1.0 ml/min, the allowed leakage amount.

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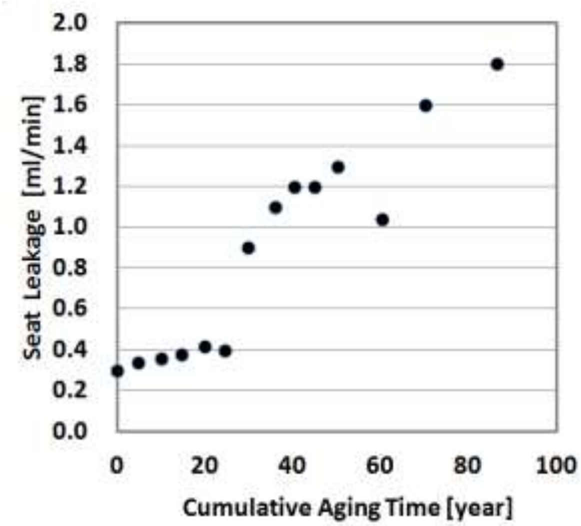

Fig. 11. Seat leakage

Figure 12 shows the results of the valve stem leakage test. The horizontal axis is the number of cumulative years for valve aging (number of operating years), and the vertical axis is the leakage pressure (bar). According to the figure, it is found that the leakage pressure (leakage amount) of the stem increases as the number of operating years increases.

The leakage pressure of the valve stem increases in two steps as the number of operating years increases. That is, it is rapidly increased until 20 years of operating and it is gradually increased thereafter. From this, since the packing which determines the leakage of valve stem is rapidly deteriorated until 20 years of operating, it is determined that the lifespan of the packing is up to 20 years.

Since the leakage of stem is strictly restricted for the valves related to the safety of nuclear power plants, it requires close attention to the maintenance of the valve stem when the operating years increase.

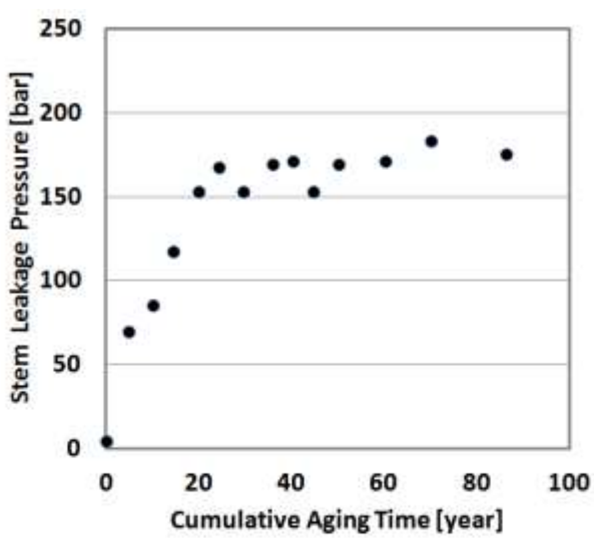

Fig. 12. Stem leakage

ISSN: 2277-9655
Impact Factor: 4.116

Accelerated Radiation Aging

Figure 13, 14 and 15 show results of the valve actuator, stem and seat leakage test. From the figures, it was found that there is almost no change in the valve actuator, stem, seat leakages amount as the years of operation increase. Therefore, it was proved that the radiation aging of valves rarely have an effect on valve actuator, stem and seat leakage.

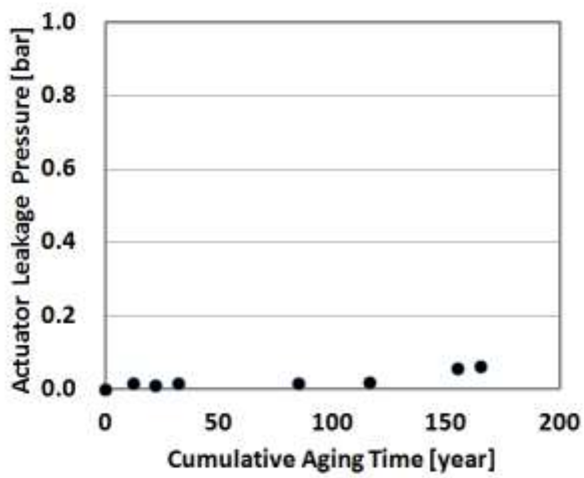

Fig. 13. Actuator leakage

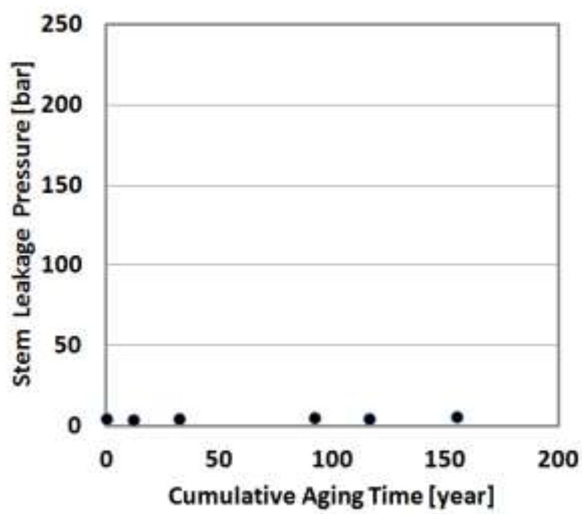

Fig. 14. Stem leakage

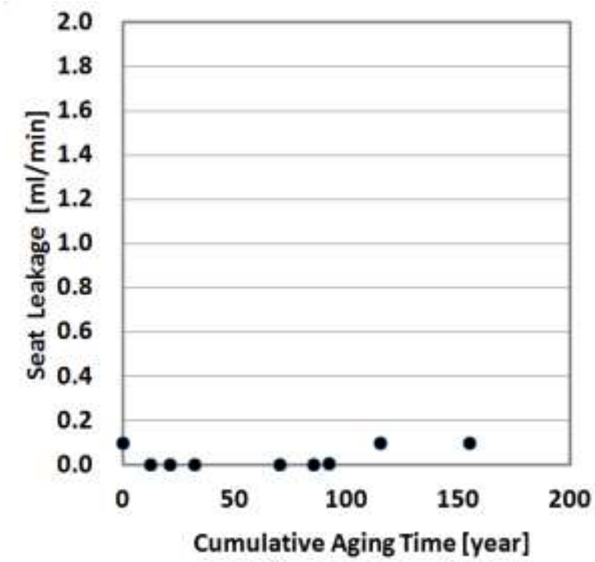

Fig. 15. Seat leakage

Meanwhile, Figure 16 shows the stroke time measurement test results. As shown in the figure, the stroke speed was constant at 7.0 mm/sec as the years of operating valve increase. Therefore, it was found that the radiation aging rarely affects on the stroke time of valve.

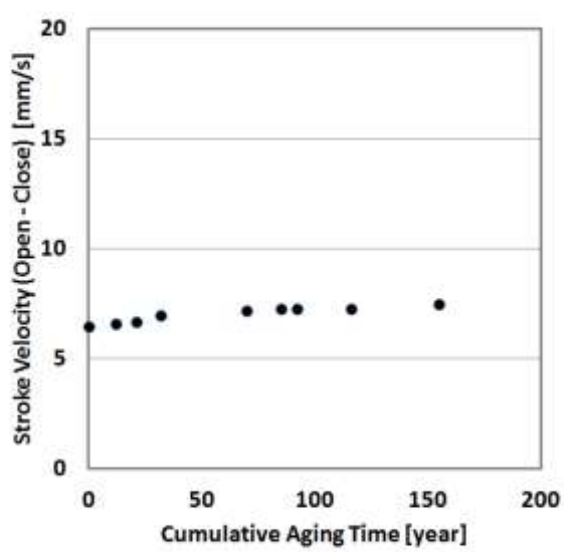

Fig. 16. Valve stroke time

Accelerated Mechanical Aging

Figure 17, 18 and 19 show results of the valve actuator, stem and seat leakage test. From the figure, it is found that the mechanical aging of the valve rarely affects the valve actuator and valve seat leakage. Provided, however, that the valve stem leakage tends to be slightly increased as the mechanical aging is progressed. But it is still insignificant compared to thermal aging specified in 3.2 (Fig. 18).

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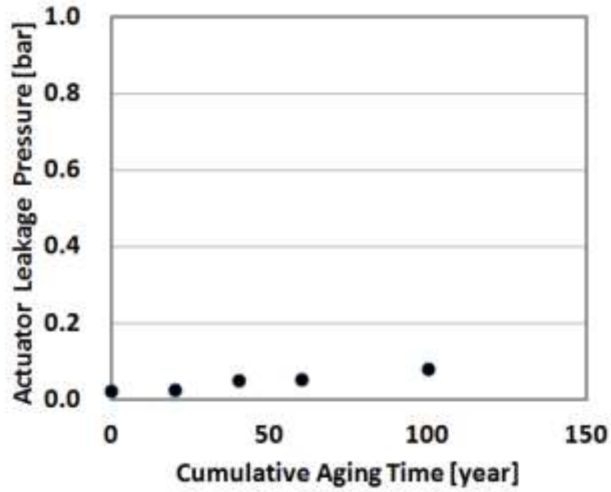

Fig. 17. Actuator leakage

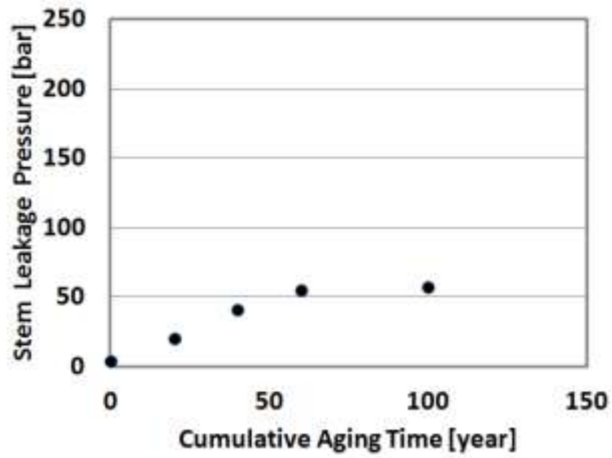

Fig. 18. Stem leakage

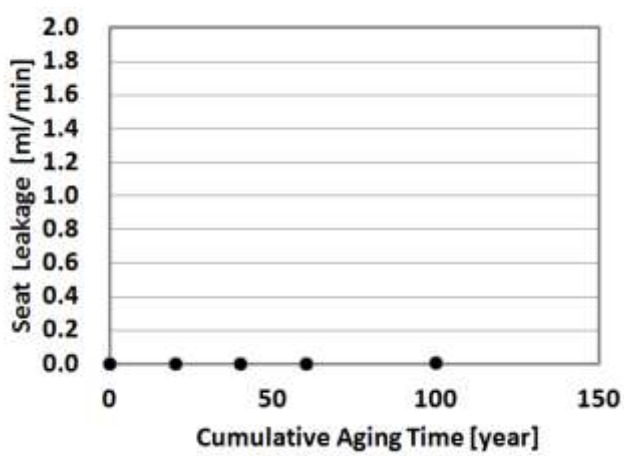

Fig. 19. Seat leakage

Meanwhile, Figure 20 shows the stroke time measurement test results. According to the figure, the stroke speed was constant at 6.5 ~ 7.0 mm/sec as the years of operating valve increase. Therefore, it was found that the mechanical aging rarely affects on the stroke time of valve.

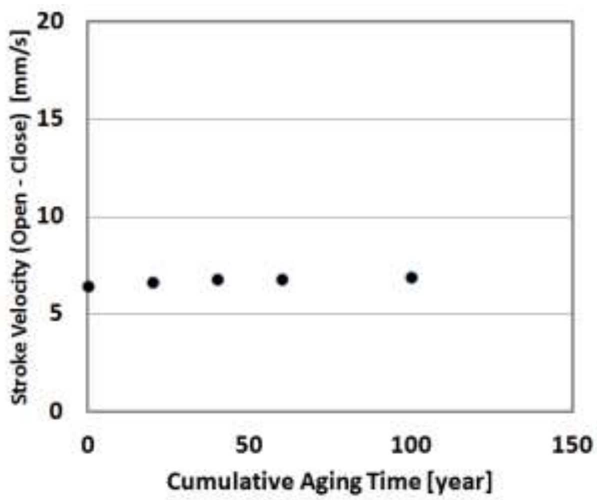

Fig. 20. Valve stroke time

CONCLUSION

In order to establish measures to secure reliability of valves used in nuclear power plants, according to the technical standards of KEPIC or ASME, the initial basic performance tests were conducted to check the performances. Then, the leakage and stroke time were measured by performing an accelerated life test (thermal aging, radiation exposure, mechanical cycling) under the operating conditions of the power plants. The results are summarized as follows:

(1) The aging factor which carries the most significant impact on valve performance is heat (temperature). Radiation and mechanical aging rarely affect on the performance of valves.
(2) While thermal aging of valve significantly affects the valve seat and stem leakage, it does not have any significant effect on actuator leakage and stroke time.
(3) In particular, valve seat leakage exceeded the allowed leakage amount at 30 years of aging years (years of operation).
(4) The packing which determines stem leakage becomes rapidly deteriorated around 20 years of aging (the number of operating years), so the lifespan is determined to around 20 years.

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