# Leakage Rates of High-Temperature Water From Wet-Type Transport Casks of Spent Fuel

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## INTRODUCTION

In Japan, a program for enhancement of fuel burnup in their cores has been promoted as one of the sophistication programs of light water reactors to reduce fuel cost and to minimize the amount of spent fuel generated. To be consistent with this program, a new wet-type transport cask has been developed to ship the high burnup spent fuels effectively (e.g., Kokaji et al. 1992).

A sealing function is essential for transport casks of radioactive materials in transport to prevent radioactive materials from being released into the environment. The evaluation method on the release rate has been standardized by the ISO. For a lack of highly accurate data on high temperature water leakage rates of $10^{-4}$ to $0.1 cm^3/s$, which are closely related to the sealing performance of wet-type transport casks of spent fuels, the appropriateness of the evaluation method on the leakage rate specified in the standardization has never been verified.

In this work, leakage rates of high temperature water from capillary tubes, whose configurations and dimensions were known, were first investigated experimentally to understand the vaporization effect of superheated water on the leakage rate. Next, the leak paths subjected to a preshipment leak test were simulated by a scratch on an O-ring surface and very thin wires adhering to an O-ring surface. High temperature water leakage rates from these simulated leak paths were investigated to establish an evaluation method of leakage rates from a noncircular leak path and multiple leak paths.

## EXPERIMENTAL APPARATUS

Figure 1 shows an outline of the experimental apparatus composed of an isothermal tank, a test tube, a preheat tank, a high temperature water supply line, a pressure regulator system, and a differential pressure measurement system. The isothermal tank was filled with water and cartridge heaters were installed at its lower flange. The isothermal tank is covered sufficiently with thermal insulator to restrain heat loss. Two pressure regulation systems were adopted to regulate the pressures in both the test tube and the isothermal tank, respectively. Each pressure regulation system was composed of a nitrogen gas cylinder, a decompression valve, and a pressure regulation valve.

The test section is shown in Figure 2, which was made of a stainless steel tube (8mm

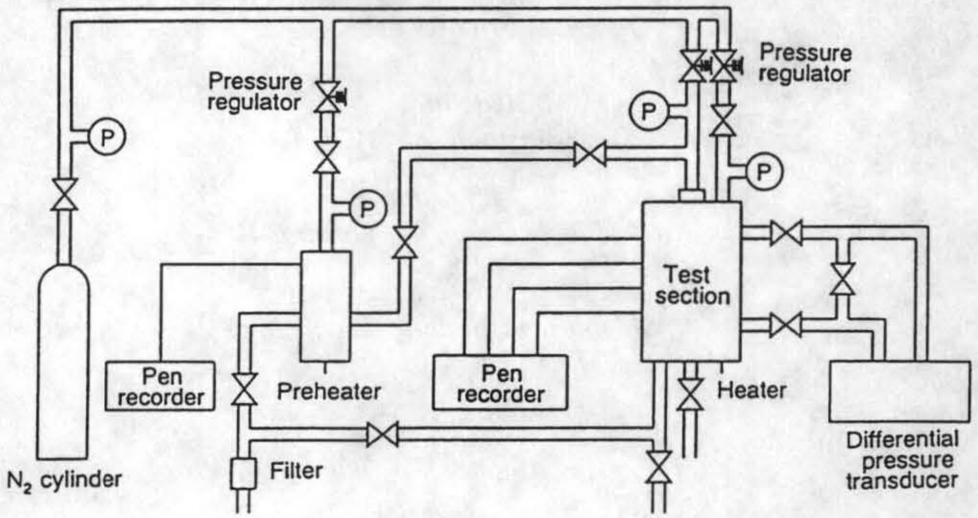

Fig.1. An Outline of Experimental Apparatus

O.D., 6mm I.D.) and installed vertically in the isothermal tank. A flange is attached to the lower part of the test tube to mount a simulated leak path on it. The leak path was simulated by (1) capillary tubes whose configuration and dimension were known, (2) a scratch on an O–ring surface, and (3) very thin wires adhering to an O–ring surface. A mirror finished surface of a disk of 20mm in diameter and 5mm in thickness was scratched artificially by a diamond needle in radial direction with uniform depth. Thin stainless steel wires of 50$\mu$m and 100$\mu$m were used as the leak paths which simulated hairs adhering to an O–ring surface, since a hair diameter is 50$\mu$m to 150$\mu$m.

Tap water was fed through an ion exchanger and a 5$\mu$m–meshed filter into the preheat tank, was pressurized, heated, and degassed therein. This water was supplied to the test tube. After the water temperature in the isothermal tank was regulated to the desired value, the experimental apparatus was kept constant for 1 hour to stabilize the water temperature in the test tube. The valve attached to the lower part of the flange was opened and the water in the test tube was discharged through the leakage path. The experiment conditions are summarized in Table 1.

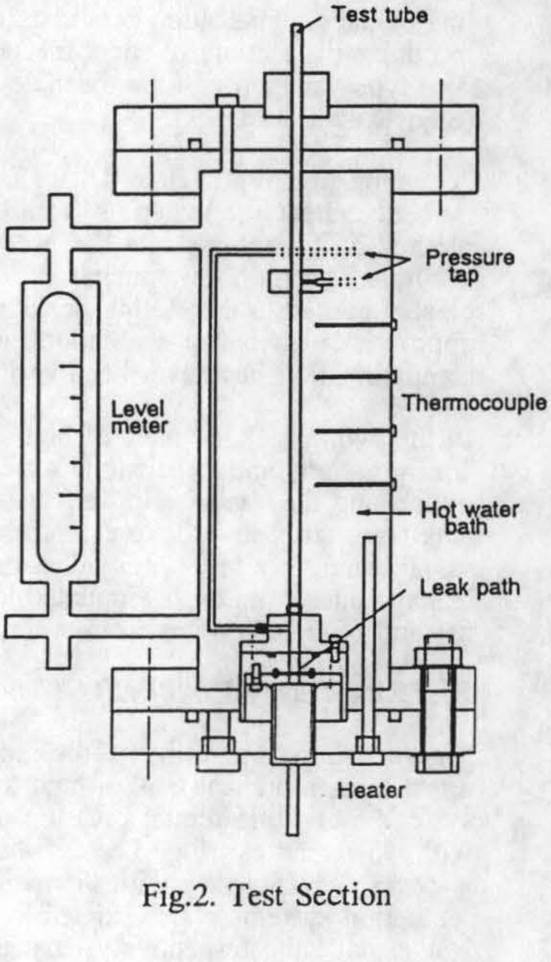

Fig.2. Test Section

Table 1. Experimental Conditions

| | |
|---|---|
| Working fluid | Ion-exchange water |
| Water temperature | 20, 120 - 180°C |
| Discharged pressure | 0.2 - 1.4MPa |
| Backpressure | Atmospheric pressure |
| Simulated leak paths | |
| Orifice diameter | 50.0 $\mu$m |
| Capillary tube diameter | 20.0, 50.0, 130.0 $\mu$m |
| Scratch | - |
| Wire diameter | 50, 100 $\mu$m |

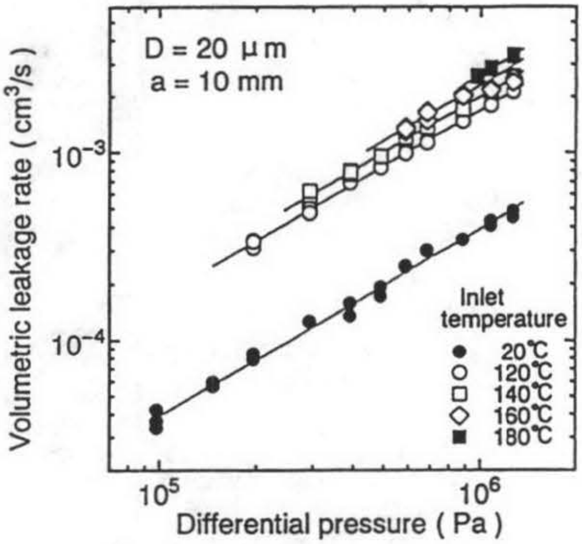

Fig.3. Volumetric Leakage Rates from Capillary Tube (D=20 $\mu$m, a=10mm)

## LEAKAGE RATES FROM CAPILLARY TUBES

The leakage rates of water under high pressures and at high temperatures were investigated experimentally from capillary tubes. The experimental results from a capillary tube of 20 $\mu$m diameter and 10mm long are shown in Figure 3. It can be seen from the figure that the volumetric leakage is proportional to the differential pressure between the upstream and downstream pressures and that the leakage rate increases as the discharged water temperature becomes higher.

The friction loss of a flow in a channel can be expressed by

$$P_u - P_d = \lambda \frac{1}{2} \rho u^2 \frac{a}{D} , \tag{1}$$

where $P_u$ and $P_d$ are the upstream and downstream pressures, $\lambda$ the friction factor, $\rho$ the water density, $u$ the velocity in a leak path, and $a$ and $D$ the length and the inner diameter of the test tube. The friction factors are expressed by

$$\lambda = 64 / Re , \tag{2}$$

for a laminar flow and by

$$\lambda = 0.3164 / Re^{0.25} , \tag{3}$$

for a turbulent flow, where *Re* is the Reynolds number. The following evaluation equation of liquid leakage rates is specified in ANSI N14.5 (ANSI 1987) assuming the laminar flow governed by the friction loss:

$$Q = \frac{\pi D^4}{128 \mu a} ( P_u - P_d ) . \tag{4}$$

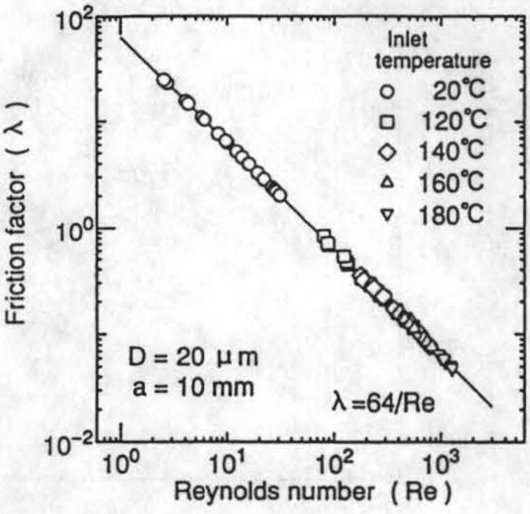

Fig.4. Friction Factor for Leakage from a Capillary Tube (D=20 $\mu$m, a=10mm)

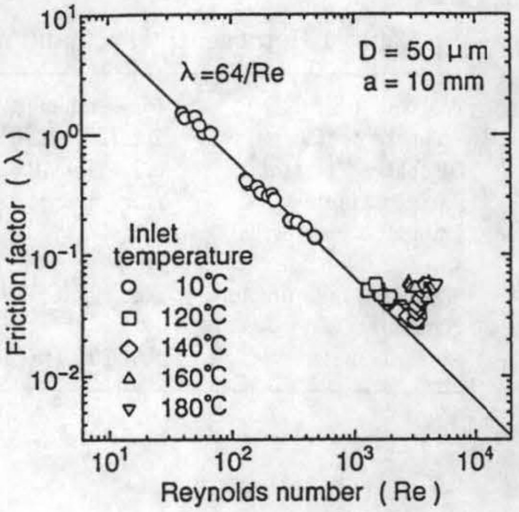

Fig.5 Friction Factor for Leakage from a Capillary Tube (D=50 $\mu$m, a=10mm)

A comparison of the friction factors calculated from the experimental results with Eq.(2) is shown in Figure 4. Equation (2) agrees well with the experimental results. It can be said from these results that in a very narrow leak path with 20 $\mu$m in diameter and 10mm long the self-flashing is not induced even for high temperature water and that the flow can be regarded as a laminar flow governed by the friction loss.

In order to understand the effect of the tube diameter on the leakage rate of high temperature water, the tube length of 10mm was kept while the diameter of 50 $\mu$m was chosen. The friction factors obtained from the experimental results are shown in Figure 5 as compared with Eqs.(2) and (3). The experimental results can then be explained by considering that a laminar flow is turned to a turbulent one at $Re=1,000$.

For the tube of 10mm long, it cannot be clear whether the self-flashing is induced or not because the flow regime is in the transition region between a laminar and a turbulent flows. Hence, the capillary tube of 60mm long was chosen to get the Reynolds number less than 1,000. Figure 6 shows a comparison of the friction factor obtained from the experimental results with Eq.(2). Equation (2) agrees well with the experimental results for room temperature water, but is smaller than the experimental ones for high temperature water and is almost shifted in parallel. This fact indicates that a choked flow is induced by the self-flashing of superheated water so that the volumetric leakage rate is reduced.

Next, the time passing through the superheated region in a capillary tube is analyzed. From the velocity obtained from the experiment and Eq.(1), the length from the inlet of the leak path to the point, $z_s$, where the pressure is equal to the saturation one of the discharged water, can be calculated. The time passing through the superheated region, $\tau_s$, is calculated by $z_s$ and the velocity. It can be distinguished from the friction factor whether a choked flow appears or not. Figure 7 shows this distinction against the time passing through the superheated region. The self-flashing is induced for $\tau_s$ longer than 3ms but is not induced for $\tau_s$ shorter than 3ms.

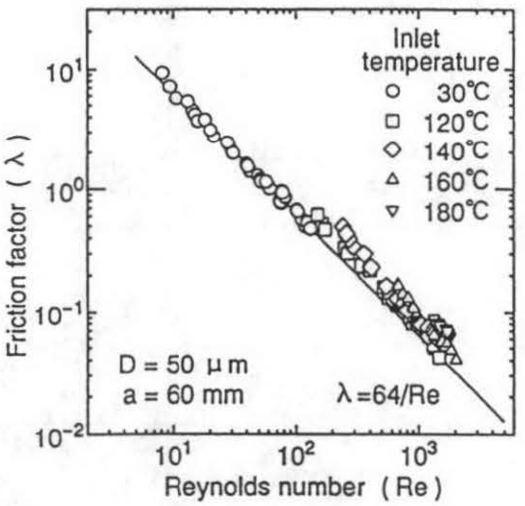

Fig.6. Friction Factor for Leakage from a Capillary Tube (D=50$\mu$m, a=60mm)

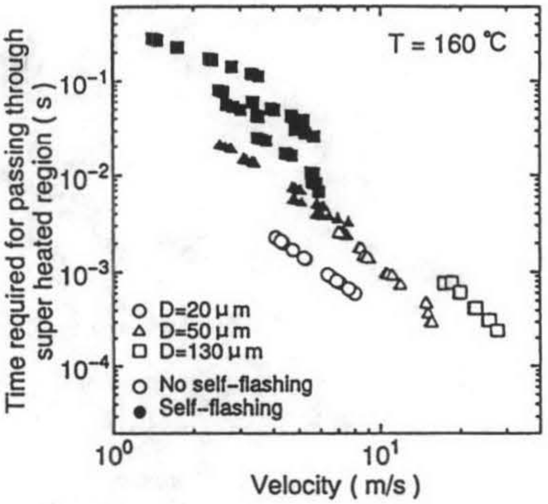

Fig.7. Effect of Time Passing through Superheated Region and Self-Flashing Occurrence

## LEAKAGE FROM A SCRATCH ON THE SURFACE OF AN O-RING FLANGE

Leakage rates of high temperature water from the leak path simulated by a scratch induced artificially in a radial direction on the disk surface were experimentally investigated and the results are shown in Figure 8. Provided that the leakage path could be approximated by a circular tube in the same manner as specified in ANSI N14.5 and that the self-flashing in the leakage path could be ignored, the volumetric leakage rate of water with high pressure and temperature can be evaluated by Eq.(4). Rewriting Eq.(4),

$$\frac{D^4}{a} = \frac{128\mu Q}{\pi(P_u - P_d)} . \tag{5}$$

The characteristic value of the leak path, $D^4/a$, is calculated by substituting the measured leakage rates to Eq.(5) as shown in Figure 9. An averaged $D^4/a$ was calculated at $4.14\text{x}10^{-18}\text{m}^3$. The solid line shown in the Figure 8 was obtained by substituting this value to Eq.(4). When a pair of flanges were tightened, the O-ring was deformed in the same shape as the groove. Supposing that the leak path length is the width of the groove (3.2mm), the equivalent diameter of the leak path was 10.75$\mu$m.

An experiment was also carried out to measure leakage rates of water with room temperature from a thinner scratch than that mentioned above, which was visible. The volumetric leakage rate for the differential pressure of 1.4MPa was less than $10^{-5}\text{cm}^3/\text{s}$.

## LEAKAGE FROM THIN WIRES ADHERING TO AN O-RING SURFACE

No evaluation method has been established for leakage rates of high temperature water from multiple leak paths. It is supposed from the above results that self-flashing can be neglected and the leakage behavior is governed by a laminar flow provided that the leak path length is less than 10mm. In the case where there are n leak paths, the leakage rate from each leak path is supposed to be evaluated by

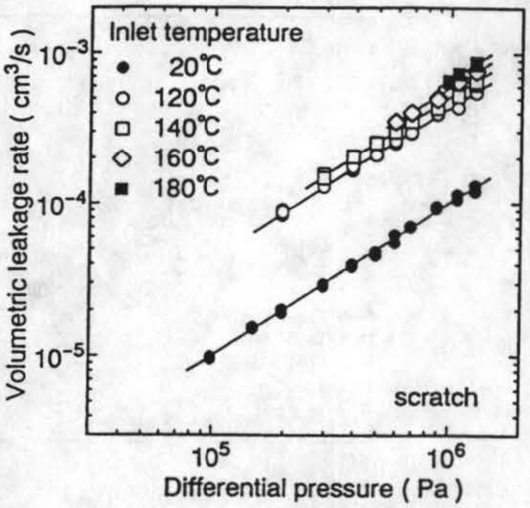

Fig.8. Volumetric Leakage Rate from an Artificial Scratch on a Seal Surface of O–ring Flange

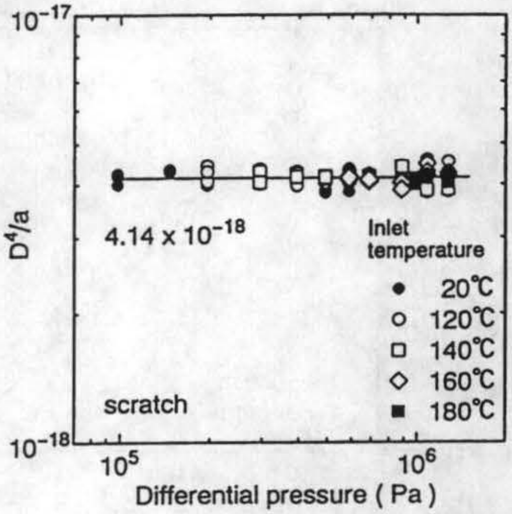

Fig.9. The Characteristic Value of Leak Path Formed by a Scratch on a Seal Surface of O–ring Flange

$$Q_i = \frac{\pi D_i^4}{128\mu a_i}( P_u - P_d ) , \tag{6}$$

where *i* indicate "i"th leak path. Since the upstream and downstream conditions (pressures and temperatures) are equal for all leak paths, the total volumetric leakage rate can be obtained by

$$Q = \sum_{i=1}^{n} Q_i = \frac{\pi( P_u - P_d )}{128\mu}\sum_{i=1}^{n}(\frac{D^4}{a})_i \tag{7}$$

Then, the characteristic value of multiple leak paths is determined by

$$\frac{D^4}{a} = \sum_{i=1}^{n}(\frac{D^4}{a})_i \tag{8}$$

The total volumetric leakage rate can be also rewritten by the same expression for single leak path which is Eq.(4).

Leakage rates of high temperature water from leak paths, which were formed by a stainless steel wire of 100 $\mu$m in diameter adhering to the O–ring surface, were experimentally investigated and the results are shown in Figure 10. The $D^4/a$ is calculated by Eq.(8) and an averaged $D^4/a$ is $1.85 \times 10^{-17}$m³. The solid lines shown in Figure 10 were obtained by substituting this value to Eq.(4). Assuming that the leakage path length is the width of the groove, the equivalent diameter of the leakage path is 15.6 $\mu$m.

In addition, leakage rates of high temperature water from leak path formed by a 50 $\mu$m stainless steel wire adhering to the O–ring surface were investigated. No significant change of differential pressure was observed even after 60 hours.

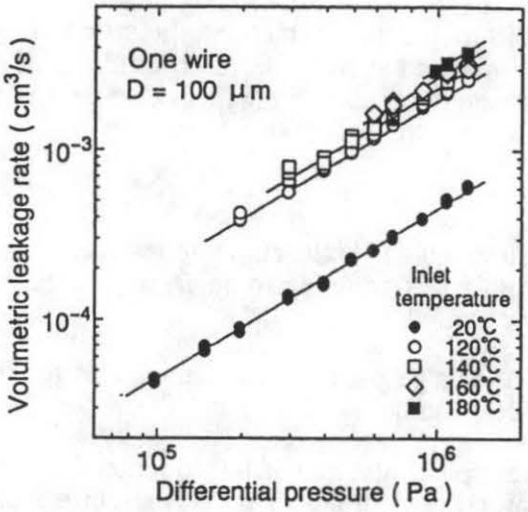

Fig.10. Volumetric Leakage Rate from Leak Paths Formed by Wires Adhering to O–ring Surface

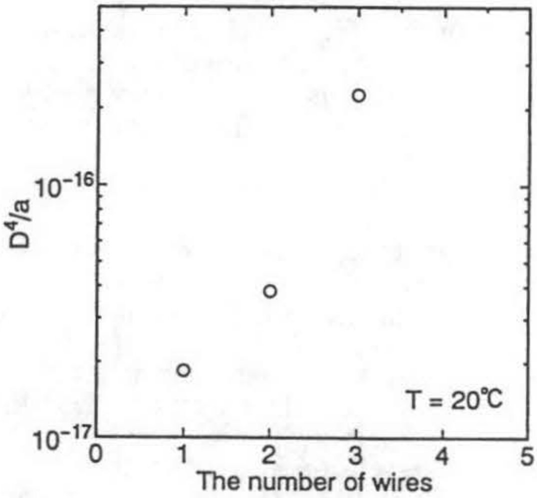

Fig.11. The Characteristic Value of Leak Paths Formed by a Wire Adhering to O–ring Surface

Leakage rates from multiple leak paths simulated by two and three 100 $\mu$m stainless steel wires adhering to the O–ring surface were also investigated experimentally. The $D^4/a$ is calculated by Eqs.(4) and Eq.(6). The average $D^4/a$ are $3.86\times10^{-17}$m$^3$ in the two–wire case and $2.27\times10^{-16}$m$^3$ in the three–wire case. The effect of the number of wires on the $D^4/a$ is shown in Figure 11. Moreover, the equivalent diameters of the leakage paths are 18.7 $\mu$m in the two–wire case and 29.2 $\mu$m in the three–wire case. It is supposed that there are two leak paths formed at both sides of the wire in the single wire case, four leak paths created at the both sides of the wires in the two–wire case, and six leak paths in the three–wire case. Provided that the experimental condition and the leak path characteristic are the same, the volumetric leakage rate in the two–wire case is twice that in the single wire case. Since the $D^4/a$ in the two–wire case is 2.09 times that in the single wire case, the condition of tightening the flanges was almost the same in both cases. In contrast with this, the $D^4/a$ in the three–wire case is 12.3 times that in the single wire case. This fact indicates that the flange could not be fastened as tightly as other cases and the cross section of each leak path formed by three wires increased.

From this work and our previous works on gas leakage rate (Aritomi et al. 1993. 1994, 1995), it is clarified that the self–flashing can be neglected for the volumetric leakage rate of high temperature water with a range of $10^{-4}$ to 0.1cm$^3$/s, which is in the same range of the leakage rates from a defect on the seal surface of the O–ring flange or valve sheet subjected to the preshipment leak test. Consequently, the leakage rate which is closely related to the containment performance of a transport cask can be evaluated by

$$Q = \frac{\pi D^4}{128\mu a\beta}(P_u - P_d) \tag{9}$$

where $\beta$ is the expansion coefficient. $\beta$ is 1.0 for liquid and is expressed by

$$\beta = 2P_u / (P_u + P_d) \tag{10}$$

for gas. Since each transport cask adopts a different leak test method, the criteria required in each cask are also different. The $D^4/a$ is proposed as a standardized criterion of a leak test which is universal among all leak test methods because Eq.(8) can also be applied to the leakage rate from a noncircular leak path and multiple leak paths.

## CONCLUSIONS

The leakage rates of water under high pressures and at high temperatures from capillary tubes, a scratch on an O–ring surface, and thin wires adhering to an O–ring surface were investigated, and the following insights are clarified:

- The flow of high temperature water from a leakage path can be regarded as a laminar flow under the condition where the Reynolds number is less than 1,000.

- The self–flashing is not induced for the time passing through the superheated region shorter than 3ms and the flow can be regarded as a single phase flow. On the other hand, the self–flashing is induced at the exit of a leakage path and a choked flow appears for the time longer than 3ms. Consequently, the leakage rate becomes less than the result evaluated as a single phase flow.

- Even for a noncircular leak path and multiple leak paths which are supposed for practical leak paths of transport cask, the leakage rate of high temperature water in both normal and accidental conditions in transport can be calculated in the same evaluation method as specified in ANSI N14.5, as long as the characteristic value of leak paths ($D^4/a$) is obtained from the leakage rate measured at a preshipment test. Since the volumetric leakage rate of gas or liquid in a range of $10^{-4}$ to $10^{-2}$cm$^3$/s, which is closely related to the containment performance of the transport cask, can be evaluated by the correlation of the friction loss in a laminar flow, the $D^4/a$ is proposed as an universal evaluation to express the criteria of the preshipment test.

- In the case where no scratch is observed or an adhesion like a hair whose diameter is less than 50$\mu$m to an O–ring surface, the high temperature water leakage rate is less than $10^{-4}$ cm$^3$/s.

This work was performed at the Tokyo Institute of Technology in collaboration with Hitachi Zosen Corp.

## REFERENCE

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