BENCHMARK CALCULATIONS FOR EVALUATION METHODS OF GAS VOLUMETRIC LEAKAGE RATE

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SUMMARY

A containment function of radioactive materials transport casks is essential for safe transportation to prevent the radioactive materials from being released into environment. Regulations such as IAEA standard determined the limit of radioactivity to be released. Since it is not practical for the leakage tests to measure directly the radioactivity release from a package, a gas volumetric leakage rates are usually measured instead. Methods of evaluating gas volumetric leakage rates are proposed in ANSI N14.5 and ISO standards. In our previous works, gas volumetric leakage rates for several kinds of gas from various leaks were measured and two evaluation methods, “a simple evaluation method” and “a strict evaluation method”, were proposed based on the results. The simple evaluation method considers the friction loss of laminar flow with expansion effect. The strict evaluating method considers an exit loss in addition to the friction loss. In this study, four worked examples were completed for on assumed large spent fuel transport cask (Type B Package) with wet or dry cavity and at three transport conditions; normal transport with intact fuels or failed fuels, and an accident in transport. The standard leakage rates and criteria for two kinds of leak test were calculated for each example by each evaluation method. The followings observations are made based upon the calculations and evaluations:

- The choked flow model of ANSI method greatly overestimates the criteria for tests.
- The laminar flow models of both ANSI and ISO methods slightly overestimate the criteria for tests
- The above two results are within the design margin for ordinary transport condition and all methods are useful for the evaluation.
- For severe condition such as failed fuel transportation, it should pay attention to apply a choked flow model of ANSI method.

INTRODUCTION

A containment function of transport casks of radioactive materials such as spent fuels is essential to prevent radioactive materials from being released excessively into the environment. A limit of the radioactivity release is defined by both domestic regulations and International Atomic Energy Agency (IAEA) standard (1996) and the containment function is required to be confirmed not only at transport but at design, fabrication and maintenance stages. It is not practical for containment tests such as pre-shipment test to measure directly a radioactivity release so that gas volumetric leakage rate is usually assessed instead of the radioactivity release. A gas leakage rate required for the containment function of a spent fuel transport cask is in the range of 10^{-10} to 10^{-7} m^3/s, where a continuum flow is dominant and molecular flow can be neglected. Therefore, a flow regime discussed in this paper is limited to a continuum flow.

Based on the presume that a leak is circular capillary tube, ANSI N 14.5 (1987) and ISO 12807 (1996) standards propose an evaluation method respectively to assess a volumetric leakage rate from a maximum radioactivity release rate which is drawn step by step in accordance with the procedures specified in the standards. In our previous works (Aritomi et al., 1993,1994) gas volumetric leakage rates for several kinds of gas from various leaks were measured and two evaluation methods, "a simple evaluation method" and "a strict evaluation method", were proposed to explain the experimental results. The simple evaluation method considers a friction loss of laminar flow with gas expansion effect. The strict evaluating method considers exit loss in addition to the friction loss with gas expansion effect in the capillary tube.

In this work, each evaluation method is explained. Four worked examples are proposed as typical cavity conditions of either wet or dry type spent fuels transport cask. A standard leakage rate and test criteria for two kinds of leakage test conditions are evaluated by each method. The results are compared and discussed on an applicability of the methods for assessment of leakage rates.

EVALUATION METHOD

ANSI N14.5 1987 (ANSI method)

A volumetric leakage rate is used in this standard. One of two gas flow equations is used for estimating leakage rate in the range where a continuum flow is dominant. Equation 1 is used for estimating volumetric leakage rate (m^3/s) when (P_d/P_u) is greater than a critical pressure ratio, r_c (the flow is not choked) and equation 2 is used for (P_d/P_u) less than or equal to r_c (choked). The critical pressure ratio is defined in equation 3. Equation 1 is derived from Hargen Poiseuille's law and equation 2 from orifice choked flow.

$$L = \frac{2.46 \times 10^{-2} D^4}{a\mu}(P_u - P_d) \qquad (\mathrm{m^3/s}) \qquad (1)$$

$$L = \frac{\pi D^2}{4}\sqrt{\frac{2\kappa RT}{M(\kappa+1)}}\left(\frac{2}{\kappa+1}\right)^{\left(\frac{1}{\kappa-1}\right)} \qquad (\mathrm{m^3/s}) \qquad (2)$$

$$r_c = \left(\frac{P_d}{P_u}\right) = \left(\frac{2}{\kappa+1}\right)^{\left(\frac{\kappa}{\kappa-1}\right)} \qquad (3)$$

Where **D** is leak diameter (m), **a** leak length (m), μ fluid viscosity (Pa•s), **Pu** upstream pressure (Pa), **Pd** downstream pressure (Pa), **R** universal gas constant ($J \cdot mol^{-1} \cdot K^{-1}$), **T** fluid temperature (K), **M** molecular weight ($kg \cdot mol^{-1}$), κ specific heat ratio(-). Equation 1 is also proposed for evaluating a liquid volumetric leakage rate in ANSI standards.

ISO 12807 (ISO Method)

Mass-like leakage rate ($Pa \cdot m^3/s$) is used in this standard. Equation 4 is proposed for evaluating the continuum flow. It is found by multiplying the equation 1 by $(P_u+P_d)/2$ that the equation 4 is also derived from Hargen Poiseuille's law.

$$Q = \frac{1.23 \times 10^{-2} D^4}{a\mu}(P_u^{\,2} - P_d^{\,2}) \qquad (\mathrm{Pa \bullet m^3/s}) \qquad (4)$$

Equation 1 is also proposed to estimate a liquid volumetric leakage rate in ISO standard.

Simple Evaluation Method

The friction loss for laminar flow with gas expansion effect is proposed in our previous works (Aritomi, 1993 and 1994) to evaluate a continuum gas flow, which explains well the experimental results up to 10^{-7} m^3/s. The equation is expressed by equation 5, which is obtained by multiplying the equation 1 by $(P_u+P_d)/2P_u$.

$$L = \frac{\pi D^4}{128 a \mu P_u}(P_u^{\,2} - P_d^{\,2}) \qquad (\mathrm{m^3/s}) \qquad (5)$$

It is also shown in our work (Sudi et al.1997) that the equation 1 is well explains the experimental results of liquid volumetric leakage rates.

Strict Evaluation Method

Strict evaluation method based on Santeler's work (1986). A tube flow with high velocity expands from the exit of a tube against a back pressure so that the exit pressure is higher than that of downstream and this pressure drop is called an exit loss. The mass flux (kg/(m^2•s)) governed by a friction loss in the capillary is expressed by equation 6 where $\mathbf{P_t}$ is the exit pressure of a capillary (Pa), ρ_u upstream density (kg/m^3). The equation is equivalent to the equation 5. The exit loss for choked flow is presented by equation 7 and for non-choked free expansion flow is expressed by equation 8 where α is a contraction coefficient, ρ_t the exist density (kg/m^3). These equations explain the experimental results up to 5×10^{-7} m^3/s as shown in our previous works.

$$G = \frac{\left(P_d^{\,2} - P_t^{\,2}\right)\rho_u D^2}{64 \mu P_u a} \qquad (\mathrm{kg/(m^2 \bullet s)}) \qquad (6)$$

$$G = \alpha\left[\kappa\left(\frac{2}{\kappa+1}\right)^{(\kappa+1)/(\kappa-1)} P_t \rho_t\right]^{1/2} \qquad (\kappa\mathrm{g/(m^2 \bullet s)}) \qquad (7)$$

$$G = \alpha\left[\frac{2\kappa}{\kappa-1} P_t \rho_t \left\{\left(\frac{Pd}{Pt}\right)^{2/\kappa} - \left(\frac{Pd}{Pt}\right)^{\kappa+1/\kappa}\right\}\right]^{1/2} \qquad (\mathrm{kg/(m^2 \bullet s)}) \qquad (8)$$

$$L = \frac{\pi D^4}{4\rho_u} G \qquad (\mathrm{m^3/s}) \qquad (9)$$

If (P_d/P_t) is higher than the critical pressure ratio expressed by equation 3, the combination of equation 6 and 8 is applied to evaluate the leakage rate. Otherwise, the combination of equation 6 and 7 is applied. The exit pressure Pt is obtained by iterative calculation and a mass flux is converted to a volumetric leakage rate by equation 9.

Comparison of Each Method

The relationship between volumetric leakage rates and leak diameters was investigated by each method under following conditions; a working fluid is air at standard condition, leak length 10 mm, upstream pressure 7.10×10^5 Pa and downstream pressure 1.01×10^5 Pa. As the critical pressure ratio is less than r_c, the choked flow model is used in ANSI method. The results are shown in Figure 1, which indicates that the choked flow model of ANSI method greatly overestimates the leakage rate, that ISO method slightly overestimates a leakage rate and that the simple evaluation method is identical to the strict evaluation method up to 10^{-7} m^3/s.

Assuming a leak with diameter of 20 μm and length of 10 mm, and a back pressure of an atmosphere, the effect of differential pressure between upstream and downstream pressure to a volumetric leakage rate was investigated by each evaluation method. The results are shown in Figure 2. It indicates that ISO method slightly overestimates the leakage rate and that the simple evaluation method is coincident to the strict evaluation method. On the contrary, there is a discontinuity in the results of ANSI method and leakage rates suddenly increase when the critical pressure ratio meets the choked flow condition, which greatly overestimates the leakage rate. As Higson et al. (1989) pointed out, there is no physical reason for the discontinuity.

As mentioned above, the strict evaluation method explains well the experimental data up to 5×10^{-7} m^3/s and it can be used as "standard value" for comparison among the 4 evaluation methods.

WORKED EXAMPLES

Four examples shown in Table 1 are completed for bench mark calculations. Example 1 supposes the conditions of wet type cask with intact fuels under normal transport conditions and example 2 same conditions but with failed fuels. Example 3 supposes the conditions of dry type cask under normal transport conditions and Example 4 those for dry type cask at accident condition in transport. A maximum permissible leakage rate is derived from radioactivities releasable from a cask cavity in accordance with the procedures described in ANSI or ISO standard. Leakage rates under three conditions shown in Table 2 were evaluated by each evaluation method. Standard condition in the second row is the conditions for dry air at 1.01×10^5 Pa of upstream pressure, to 0 Pa of downstream pressure at 298 K of temperature, which is almost same conditions as a pressure rising method from vacuum to atmosphere. Test 1 in the third row is the conditions for pressure decreasing method with rather high upstream pressure and Test 2 in the forth row those for same method with rather low upstream pressure.

Example 1: A diameter is calculated from the maximum permissible leakage rate of water so that it is same value for each method. Results of leakage rates are shown in Table 3. Comparing the results of ISO method with standard values, the former estimates the leakage rates 1.3 to 2.0 greater than latter, mainly because of gas expansion effect. Choked flow model in ANSI method estimates order of one to two greater than the standard value. Results of simple method is almost same as the standard values.

Example 2: The maximum permissible leakage rates for Example 2 shown in Table 1 is one order smaller than that of Example 1 because of failed fuels transport conditions. However, the results of comparison among four evaluation methods are almost same as those of the example 1 as shown in Table 4.

Example 3: As working fluid in the cavity is helium gas, each method was used to calculate the leak diameter. The cavity condition does not meet the choked flow condition. Three diameters are obtained as shown in Table 5, which are close together. When the standard leakage rate and criteria of test 1 is calculated, choked flow model was applied in ANSY method which determined a greater leakage rate comparing to the other three results as shown in Table 5. ISO method estimated 1.3 to 2.0 greater than the standard value.

Example 4: A permissible leakage rate for an accident condition in transport is approximately 6000 times greater than that for normal condition of transport. The calculated standard leakage rate and two criteria for leakage tests are in the range of 10^{-7} m^3/s to 10^{-6} m^3/s where choked flow is dominant as shown in Figure 1. ISO and the simple evaluation method which are based on the laminar flow model are not valid for a leakage rate of this range. The results in Table 6 show that the values calculated by the choked flow model of ANSI method and Strict evaluation method are closer than the other two results.

DISCUSSION AND CONCLUSION

From the present work, following insights are obtained and clarified.

- The test criteria derived from the laminar flow model in both ISO and ANSI methods are 1.3 to 2.0 times greater than the standard value mainly because they ignore the gas expansion effect. The difference depend on the ratio of upstream and downstream pressures ($(P_u+P_d)/2P_u$). This means that both ISO method and the laminar flow model of ANSI method tend to determine the criteria for leakage test by 1.3 to 2.0 times greater than the standard value. On the other hand, the test criteria determined by the choked flow model of ANSI method is one order greater than the standard value. However, the difference of these range is usually within the design margin for normal transport condition of spent fuel transport cask and all methods can be said useful for the determination of a criteria for leakage test of the cask.
- The criteria derived from the choked flow model of ANSI method with small leak diameter like example 2 becomes more than two orders times greater than the standard value. This indicates that it should pay attention to determine the criteria of leakage test for severer condition such as failed fuel transport because that the design margin is usually smaller than that for an ordinary transport conditions.
- The maximum leak diameter for a dry cask derived by each method is different but close to each other and the test criteria are still within the range of twice of factor 2. Consequently, it can be conclude that all method is valid for determination of a criteria for leakage test of the cask.
- For leakage rate above 10^{-7} m^3/s which is obtained from an accident condition in transport such as Example 4, laminar flow model of both ISO and ANSI methods and simple evaluation method greatly overestimate the criteria and are not valid. The result of the choked flow model of ANSI method is rather closer to the standard value. However, design margin at accident condition in transport is usually much greater than that of normal transport because an allowable radioactivity release is approximately 6000 times greater than that of normal transport condition. Therefore, it can be concluded that all evaluation method is still valid for determination of a criteria for leakage test of the cask.

REFFERENCES

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Table1 Cask Cavity Conditions

	Example 1	Example 2	Example 3	Example 4
Working Fluid	water		He	
Maximum Permissible Leakage Rate (m^3/s)	3.29E-9	9.16E-11	2.15E-9	1.76E-6
Leak Length: a (m)	1.00E-2		5.0E-3	
Upstream Pressure: P_u (Pa)	4.30E+5		1.21E+5	6.06E+5
Downstream Pressure: P_d (Pa)	1.01E+5			
Temperature: T (K)	380		353	573
Viscosity: μ (Pa•s)	2.63E-4		1.92E-5	3.03E-5
Molecular Weight: M ($kg•mol^{-1}$)	—		4.0E-3	
Specific Heat Ratio: κ	—		1.66	
Critical Pressure Ratio: Pc (-)	—		0.487	
Gas Constant: R ($J•mol^{-1}•K^{-1}$)	—		8.31	

Table 2 Standard and Test Conditions

	Standard Condition	Test 1	Test 2
Tracer Fluid	air		
Upstream Pressure: P_u (Pa)	1.01E5	6.50E5	1.80E5
Downstream Pressure: P_d (Pa)	0.0E5	1.01E5	
Temperature: T (K)	298		
Viscosity: μ (Pa•s)	1.85E-5		
Molecular Weight: M ($kg•mol^{-1}$)	2.90E-2		
Specific Heat Ratio: κ	1.4		
Critical Pressure Ratio: Pc (-)	0.528		
Gas Constant: R ($J•mol^{-1}•K^{-1}$)	8.31		

Table 3 Calculated Diameter and Leakage Rate for Example 1

	Diameter (m)	Standard Leakage Rate: L_{SLR}(m^3/s)	Criteria Leakage Rate (m^3/s)	
			TEST 1	TEST 2
ISO	3.22E-5	1.469E-8	7.955E-8	1.141E-8
ANSI		▨ 1.629E-7	▨ 1.629E-7	1.141E-8
Simple Evaluation		7.343E-9	4.597E-8	8.915E-9
Strict Evaluation		▨ 7.334E-9	▨ 4.250E-8	8.887E-9

▨ : Choked flow condition

Table 4 Calculated Diameter and Leakage Rate for Example 2

	Diameter (m)	Standard Leakage Rate: L_{SLR}(m^3/s)	Criteria Leakage Rate (m^3/s)	
			TEST 1	TEST 2
ISO	1.316E-5	4.097E-10	2.219E-9	3.183E-10
ANSI		▨ 2.722E-8	▨ 2.722E-8	3.183E-10
Simple Evaluation		2.049E-10	1.283E-9	2.487E-10
Strict Evaluation		▨ 2.049E-10	1.280E-9	2.487E-10

▨ : Choked flow condition

Table 5 Calculated Diameter and Leakage Rate for Example 3

	Diameter (m)	Standard Leakage Rate: L_{SLR}(m^3/s)	Criteria Leakage Rate (m^3/s)	
			TEST 1	TEST 2
ISO	2.550E-5	1.155E-8	6.261E-8	8.975E-9
ANSI	2.550E-5	▨ 1.022E-7	▨ 1.022E-7	8.975E-9
Simple Evaluation	2.605E-5	6.291E-9	3.939E-8	7.638E-9
Strict Evaluation	2.605E-5	▨ 6.278E-9	▨ 3.444E-8	6.978E-9

▨ : Choked flow condition

Table 6 Calculated Diameter and Leakage Rate for Example 4

	Diameter (m)	Standard Leakage Rate: L_{SLR}(m^3/s)	Criteria Leakage Rate (m^3/s)	
			TEST 1	TEST 2
ISO	6.753E-5	5.682E-7	3.078E-6	4.414E-7
ANSI	▨ 5.230E-5	▨ 4.299E-7	▨ 4.299E-7	4.414E-7
Simple Evaluation	7.726E-5	4.867E-7	3.047E-6	5.910E-7
Strict Evaluation	▨ 8.139E-5	▨ 5.427E-7	▨ 8.311E-7	5.017E-7

▨ : Choked flow condition

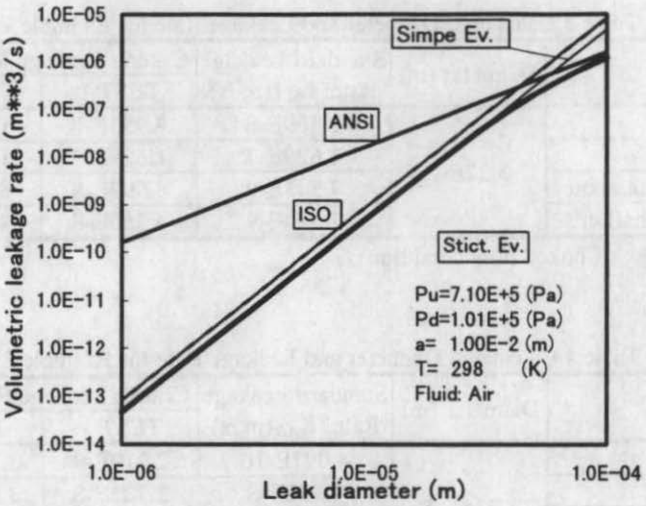

Figure 1 Comparison among evaluation methods in reference to leak diameter

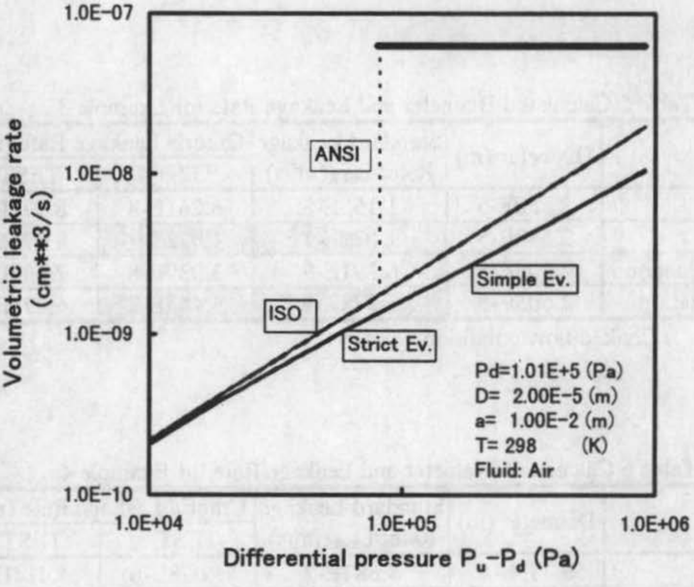

Figure 2 Comparison among evaluation methods in reference to upstream pressure

SESSION 6.4

New Regulations