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# Review of Errors of Containment Integrated Leak Rate Test for Nuclear Power Plants

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## 1. Introduction

In the system of defence in depth being applied in nuclear power plants, the reactor containment envelope is the final barrier to protect the environment in cases of accidents leading to the release of radioactive materials from the primary cooling system. The effectiveness of this barrier prevented any significant radiological consequences in the case of Three Mile Island accident. Therefore, the requirements concerning the leak-tightness and integrity of containment are strict and being applied for nuclear power plants.

One of the conditions of all operating licenses for NPPs is that reactor containments shall meet the containment leakage rate test requirements. The purposes of the tests are to assure that (i) leakage through systems and components penetrating primary containment shall not exceed allowable leakage rate as specified in the technical specifications or associated bases; and (ii) periodic surveillance of reactor containment penetrations and isolation valves is performed so that proper maintenance and repairs are made during the service life of the containment, and systems and components penetrating reactor containment. Integrate Leakage Rate Test (ILRT) is performed at the design pressure of the containment and leakage rates are determined by calculating dry air mass in the containment by measuring pressure, temperature and relative humidity with applying the ideal gas law. However, there is moisture contents (i.e. water vapor) obtained at various places inside the containment so that the partial pressure of water vapor should be corrected to estimate the leakage rate, which is defined as the ratio of the mass of air escaping from the containment in 24 hours to the total mass of air under pressure in the containment.

For the leakage rate test, errors are introduced by a difference between the measured parameter and the actual value of the parameter, produced by either predictable or identifiable (system error), or unpredictable or unidentifiable (random error). Hence this study reviewed the effect of random and system errors must be considered in the data analysis.

## 2. Requirements of Leakage Testing Rate Testing

The regulatory requirements of containment leakage rate test are contained in the Notice of NSSC (Nuclear Safety and Security Commission) No 2017-24, “Technical Criteria on Reactor Containment Leakage Rate Test” and 10CFR Part 50, “Domestic Licensing of Production and Utilization Facilities,” Appendix J, “Primary Reactor Containment Leakage Testing for Water-Cooled Power Reactors.”

According to the requirements, the performance of the leak test shall be limited to periods when the plant facility is non-operational and secured in the shutdown condition under the administrative control and in accordance with the safety procedures defined in the license.

The leak test shall be conducted in accordance with the provisions of the ANSI/ANS-56.8-1994, "Containment System Leakage Testing Requirements."

## 3. Test Methodology

### *3.1 General flow models*

There are three basic models for the flow path, using the assumption that all points along the flow streamlines are at steady state.

*(a) Conservation of Momentum Equation*

$$\frac{dW_{iner,ij}}{dt} = [\,\Delta P_{ij} - \frac{C_{FC}|W_{iner,ij}|W_{iner,ij}}{\rho_u(A_{ij})^2}\,]A_{ij}/L_{ij}$$

Where,

$W_{ij}$ = total mass flow rate of gases, vapor, and homogeneously dispersed liquid coolant;
$C_{FC}$ = irreversible flow loss coefficient;
$\Delta P_{jj}$ = pressure head due to gravity for a flow path; and
$A_{ij}$ = pressure head due to gravity for a flow path.

*(b) Conservation of Mass Equation*

$$\frac{dm_{g,i,k}}{dt} = W_{in} - W_{out} + W_{ex,so} - W_{ex,si}$$

m = mass of gas, the coolant vapor, or homogeneously dispersed (non-aerosol) liquid coolant
W = mass flow rate

*(c) Conservation of Energy Equation*

$$\frac{dU_i}{dt} = q_W + q_e + q_{sub} + q_{im,boil} + q_g$$

$U_i$ = the internal energy

q = energy transfer rate

*(d) Thermodynamic State Equations*

$$U_i = \sum_{k=1}^{N_{gas}} m_k h_k(T_i) + m_v h_v(T_i, P_v) + m_\ell h_\ell(T_i, P_i) - P_i V_i$$

U = internal energy of gases, coolant vapor, and homogeneously dispersed liquid coolant
$N_{gas}$ = number of gases that are treated as ideal gases
$m_k$ = mass of gas component k
$h_k(T_i)$ = specific enthalpy of ideal gas at temperature T
$T_i$ = temperature
$P_i$ = pressure
$V_i$ = volume;

Pressure is;

$$P_i = \sum_{k=1}^{N_{gas}} \frac{R\, N_k T_i}{V_i} + P_v$$

Where,

$P_i$ = pressure in cell i;
$P_v$ = partial pressure of coolant vapor; and
$N_k$ = moles of component *k* in the free volume.

### *3.2 Calculation of the total dry air mass*

The mass point analysis technique shall be used to determine the dry air mass in the primary containment utilizing the *Ideal Gas Law*, at each time point during the test. The rate of change of air mass shall be calculated using regression analysis with least squares fit to the air mass points. The rate of change of air mass shall be converted to the leakage rate in units of percent per day (percent 24 hours) by dividing the slope of the regression line by the intercept of the regression line and multiplying the ratio obtained by negative 2400. The corresponding total dry air mass of contained air, $W_i$ shall be determined from the *Ideal Gas Law* shown:

$$W_i = \frac{144\,V}{R}\left(\frac{P_i - P_{vi}}{T_i}\right)$$

where:

$T_i$ is calculated by

$$T_i = \frac{1}{\sum_{j=1}^{M} \frac{Vf_j}{T_j}},$$

where:

M is the number of temperature sensors;

Vfj is the volume fraction represented by the jth sensor;

Tj is the absolute temperature of the jth temperature sensor paired with the jth humidity sensor at the ith interval.

$P_{vi}$ is calculated from

$$P_{vi} = T_i \sum_{j=1}^{k} \frac{P_{vj} Vf_j}{T_j}$$

Where, Pvj is the partial absolute vapor pressure represented by the jth sensor at the ith interval. k is the number of sensors used to determine vapor pressure. Hence, as increase of the partial vapor pressure, $P_{vj}$, the total dry air mass of contained air, $W_i$, will be decreased.

*(1) Calculation of vapor pressure from dew temperature*

Since vapor pressure is a function of dew temperature, the most accurate correlation is found in the ASME Steam Tables: "Thermodynamic and Transport Properties of Steam". A simpler formula is given below.

This formula is valid in the range of dew temperatures from 32°F to 122°F for water and from -58°F to 32°F for ice.

$$p_v = A \exp\left(\frac{B(T_d - 32)}{(T_d - 32) + C}\right)$$

Where the constants *A*, *B*, and *C* are given by

| <u>Water</u> | <u>Ice</u> |
|---|---|
| $A =$ 0.0886804589; | $A =$ 0.0886717535; |
| $B =$ 17.368; | $B =$ 22.452; |
| $C =$ 429.984; | $C =$ 490.59. |

When Relative Humidity (RH) sensors are used in place of sensors that measure dew temperature, the correlation below may be used to calculate the dew temperature.

$$T_d = \frac{C \times \ln\left[\frac{\mathrm{RH}}{100} \times \exp\left(\frac{B(T-32)}{(T-32)+C}\right)\right]}{B - \ln\left[\frac{\mathrm{RH}}{100} \times \exp\left(\frac{B(T-32)}{(T-32)+C}\right)\right]} + 32$$

<u>*Ideal Gas Law (changing volume)*</u>

For uncorrected dry air mass, the following definitions apply:

$$V_C = \sum_{i=1}^{N} V_i \;;\quad f_i = \frac{V_i}{V_C}$$

For corrected dry air mass, the same definitions for $V_c$ and *fi* apply, except that one of the sub-volumes is corrected for changes in a vessel's water level. If *k* is the sub-volume number of the corrected sub-volume, then

$$V_k = V_{k0} - a(c - b)$$

The volume fractions, *fi* are then calculated with the corrected volume, and all other calculations are subsequently performed.

### *3.3 Leakage rate calculations*

The theoretical basis for using least squares methods to compute a leakage rate lies in the Gauss-Markoff theorem. The least squares is given by;

$$\widehat{W}_i = At_i + B$$

Where, *B* and *A* are the intercept and the slope of the least squares line, respectively. In the calculation of *A* and *B*, the average time and the average air mass should be calculated by;

$$\bar{t} = \frac{\sum t_i}{n} \ ,$$

$$\overline{W} = \frac{\sum W_i}{n}$$

The slope, *A*, of the least squares line may be calculated by either of the following equations:

$$A = \frac{\sum (t_i - \bar{t})(W_i - \overline{W})}{\sum (t_i - \bar{t})^2} \ ,$$

$$A = \frac{n\left(\sum t_i W_i\right) - \left(\sum t_i\right)\left(\sum W_i\right)}{n\left(\sum t_i^2\right) - \left(\sum t_i\right)^2}$$

The intercept, *B*, of the least squares line can be calculated by following equations;

$$B = \overline{W} - A\bar{t} \ ,$$

$$B = \frac{\left(\sum W_i\right)\left(\sum t_i^2\right) - \left(\sum t_i\right)\left(\sum t_i W_i\right)}{n\left(\sum t_i^2\right) - \left(\sum t_i\right)^2}$$

Each $t_i$ is the elapsed time between a clock time at which the initial reading is taken and the clock time at which the $i_{th}$ reading is taken. The leakage rate is expressed as the ratio of the rate of change of mass to the calculated mass in the containment at time *t*. Therefore, if the rate of mass change is increased, the leakage rate is increased.

The Mass Point leakage rate is expressed as what is expected to be a positive number by computing;

$$L_{am} = -2400(A/B)$$

The uncertainty in the estimated value $L_{am}$ is assessed in terms of the standard deviations of *A* and *B* and their covariance, followed by the computation of a 95% upper confidence limit (UCL) about the true leakage rate.

## 4. Sensitivity Analysis on Test Environment

The containment leakage rates are determined by calculating the dry air mass in the containment by applying the ideal gas law. Nevertheless, if there is water vapor obtained at various places inside the containment, the pressure of water vapor should be considered to estimate the leakage rate because it causes a difference between the measured parameter and the actual value of the parameter, produced by predictable or identifiable effects. Hence, this sensitivity study to the test results was carried out to identify the random errors which can be affected to the measured parameter produced by predictable or identifiable.

(a) *Case 1: Wet bulb temperature, $T_{wet}$, is changeable under constant dry bulb temperature, $T_{dry}$*

If there are moisture resources in place inside the containment, the wet bulb temperature ($T_{wet}$,) is increased as shown in Table 1, It is also observed that as $T_{wet}$ increased under constant of $T_{dry}$, vapor pressure and relative humidity are also increased so that average pressure is increased and dry air mass is decreased. As energy transfer rate of vaporized moisture contents is higher (faster) than that of gases, the rate of change of mass is increased rather than dry air inside containment. Therefore, the leakage rate is increased when the moisture content is in place. It is also observed that as amount of moisture contents is increased, the wet bulb temperature and relative humidity are increased so that the leakage rate is also increased higher as shown in the second table of Table 1.

Table 1 Sensitivity analysis results for Case 1

| Dry bulb Temp.(°C) | Wetbulb Temp.(°C) | Average Press(Pi) | Average Vapor Press(Pv) | Dry air mass (Wi) | Relative Humidity (%) | Rate of change of mass | Calculated mass | Leakage rate |
|---|---|---|---|---|---|---|---|---|
| 31.08 | 23 | 28.085 | 22.540 | 8340042 | 80.26 | -30534 | 8357853 | 8.768 |
| | 25 | 31.674 | 27.492 | 6289737 | 86.80 | -33263.5 | 6309141 | 12.653 |
| Rate of change | | 1.13 | 1.22 | 0.75 | 1.08 | 1.09 | 0.75 | 1.44 |
| 31.08 | 27 | 35.659 | 32.846 | 4230181 | 92.11 | -36004.9 | 4251184 | 20.327 |
| | 20 | 23.369 | 15.791 | 11398153 | 67.57 | -26462.1 | 11413589 | 5.564 |
| Rate of change | | 1.53 | 2.08 | 0.37 | 1.36 | 1.36 | 0.37 | 3.65 |

(b) *Case 2: Dry bulb temperature, $T_{dry}$, is changeable under constant wet bulb temperature, $T_{wet}$*

Table 2 shows a case study for variable $T_{dry}$ under constant of $T_{wet}$ when a heater is working. As the dry wet bulb temperature is increased, dry air mass increase because vapor pressure and relative humidity are decreased. As aforementioned, since energy transfer rate of dry air is lower than that of vapor so that the rate of change of mass is slightly decreased rather than that of case 1.

Table 2 Sensitivity analysis results for Case 2

| Dry bulb Temp.(°C) | Wetbulb Temp.(°C) | Average Press(Pi) | Average Vapor Press(Pv) | Dry air mass (Wi) | Relative Humidity (%) | Rate of change of mass | Calculated mass | Leakage rate |
|---|---|---|---|---|---|---|---|---|
| 33.08 | 20 | 23.369 | 14.423 | 12642063 | 61.72 | -23360 | 12655690 | 4.430 |
| 31.08 | | 23.369 | 15.791 | 11398153 | 67.57 | -26462.1 | 11413589 | 5.564 |
| Rate of change | | 1.00 | 0.91 | 1.11 | 0.91 | 0.88 | 1.11 | 0.80 |
| 37.08 | 20 | 23.369 | 11.687 | 14727325 | 50.01 | -18593.1 | 14738171 | 3.028 |
| 31.08 | | 23.369 | 15.791 | 11398153 | 67.57 | -26462.1 | 11413589 | 5.564 |
| Rate of change | | 1.00 | 0.74 | 1.29 | 0.74 | 0.70 | 1.29 | 0.54 |

### (c) *Case 3: Both wet bulb temperature, $T_{wet}$, and dry bulb temperature, $T_{dry}$, are changeable*

Case 3 study considered for the case of variable $T_{wet}$ and $T_{dry}$ concurrently in the test. As an increase of both the dry and wet bulb temperatures, as increase of vapor pressure and relative humidity, amount of dry air mass is decreased so that it is caused to increase leakage rate due to increase of the rate of mass change as shown in the first table of Table 3. In the other hand, when both the dry and wet bulb temperature decreased, dry air mass is increased due to decrease of vapor pressure and leakage rate is decreased accordingly.

Table 3 Sensitivity analysis results for Case 3

| Dry bulb Temp.(°C) | Wetbulb Temp.(°C) | Average Press(Pi) | Average Vapor Press(Pv) | Dry air mass (Wi) | Relative Humidity (%) | Rate of change of mass | Calculated mass | Leakage rate |
|---|---|---|---|---|---|---|---|---|
| 33.08 | 20 | 23.369 | 14.423 | 12642063 | 61.72 | -23360 | 12655690 | 4.430 |
| 35.08 | 23 | 28.085 | 19.795 | 11047022 | 70.48 | -23969.5 | 11061005 | 5.201 |
| Rate of change | | 1.20 | 1.37 | 0.87 | 1.14 | 1.03 | 0.87 | 1.17 |
| 35.08 | 23 | 28.085 | 19.795 | 11047022 | 70.48 | -23969.5 | 11061005 | 5.201 |
| 37.08 | 25 | 31.674 | 23.366 | 10474593 | 73.77 | -23372 | 10488226 | 5.348 |
| Rate of change | | 1.13 | 1.18 | 0.95 | 1.05 | 0.98 | 0.95 | 1.03 |

## 5. Review of ILRT Results

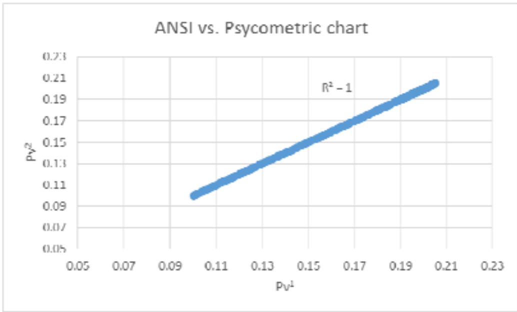
This section is discussed on the effect of random errors must be considered in the data analyses which are informed in Reference [4]. For experience of the leak rate test, it was observed some systematic errors by differences between the measured parameters and the actual values. Therefore, the following effects of random errors would be considered in the data analyses.

### (a) *Difference between Psychrometric property and ASME Steam Tables:*

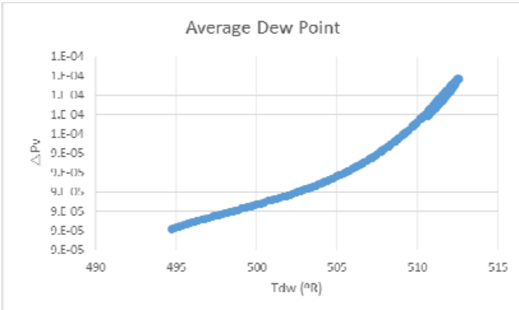
When calculates vapor pressure in the test, ANSI/ANS-56.8 uses ASME Steam Tables: "Thermodynamic and Transport Properties of Steam." which is simpler formula rather than reference empirical formula developed by Wexler in the National Bureau of Standards.

Psychrometrics is used for the field of engineering concerned with the physical and thermodynamic properties of gas-vapor mixtures which are based on empirical results.

In order to exam the accuracy of the simpler formula being used for vapor pressure calculation described in Section 2, Figure 1 (a) shows calculation results are well agreed between ANSI formula and Psycrometric data when temperature is above 0°C. However, in case of below 0°C, calculated vapor pressure using ANSI formula with constants for ice is lower than that of Psychrometric data.




(a) Case of above 0°C



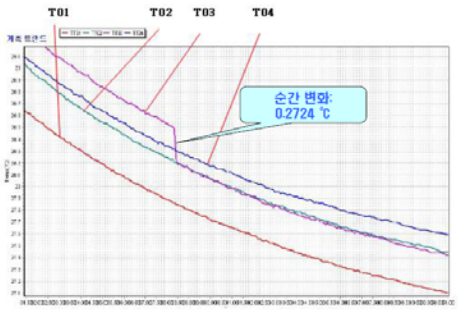

(b) Case of below 0° C

Figure 1 Comparison between ANSI and Psycrometrics

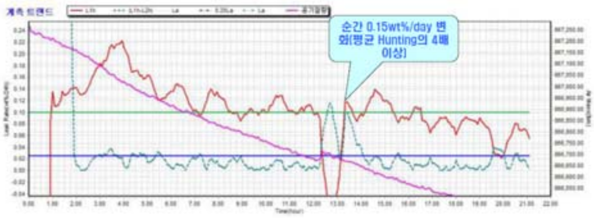
### (b) *Leakage rate change due to temperature change*

Number of temperature sensors (28 units) were installed with adjacent units, T01, T02, T03 and T04. As to T03 installed (height: 265ft, azimuth: 288 degrees, distance from center: 30ft), temperature trend and temperature are compared and concluded that T03 changed about 0.2724℃ while 28-channel average temperature change about 0.0274℃ Leak rate change in case of ILRT conducted at Shin Kori NPP (OPR Type PWR).

However, it is observed that as a decrease of temperature, leak rate was decreased accordingly. It is expected that a decrease of temperature caused by adding pressure of vapor obtained by water resources so that it leads a decrease of dry air pressure and leakage flowrates are determined by measuring the dry air pressure in the containment the ratio of the rate of change of mass as shown in Figure 2.




(a) Temperature



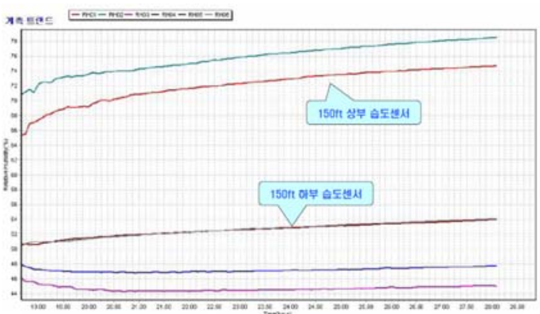

(b) Leakage rate

Figure 2 Trend of temperature and leakage rate

***(c) Operation of recirculating fan cooler***

When the fan coolers are operating, it is observed temperature difference by height. According to the test result in Figure 3, temperature difference between upper and lower temperature sensor group is about 6 ℃ and humidity difference by 15% RH. Those differences can affect to the accuracy of leakage rate measurements because the test may be conducted under thermal and mechanical non-equilibrium condition due to humidity and temperature differences.


(a) Temperature




(b) Relative humidity

Figure 3 Temperature and humidity trend of test data

***(d) Influence of water resources inside containment***

Some nuclear power plants have water resources in containment - i.e. In-containment refueling water storage tank (IRWST) at APR-1400 type NPPs, dousing tank and calandria vault at CANDU type NPPs – so that there is moisture contents produced at various places inside the containment during test. Figure 4 shows the differences of temperature and leakage rate at Shin-Kori unit 3.

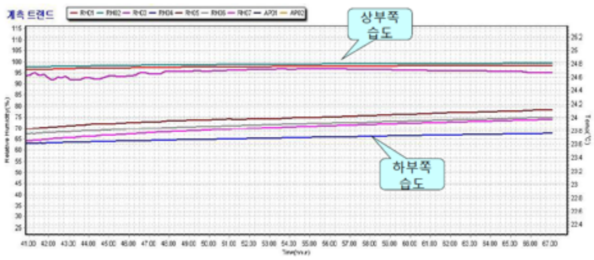



Figure 4 Difference of humidity at Shin-Kori unit 3

## 6. Conclusions

The purpose of the containment leakage rate test is to assure the leakage tightness of the reactor containment for accident conditions. Leakage rate test is performed at the design pressure of the containment and leakage flowrates are determined by measuring the dry air pressure in the containment by applying the ideal gas law. However, if there is water vapor produced from various water resources inside the containment, the measurements could be incorrected to estimate the leakage rate.

Hence this study reviewed the effect of random and system errors introduced by a difference between the measured parameter and the actual value of the parameter, produced by either predictable or identifiable (system error), or unpredictable or unidentifiable (random error).

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