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Inleakage Testing at Six South Korean Nuclear Power Plants

H.U. Kang, S.H. Kang
Korea Filter Testing Laboratory
Gwangju, South Korea

K. R. Grot, P. L. Lagus
Lagus Applied Technology, Inc.
Escondido, California

ABSTRACT

At present South Korea has 24 operating nuclear power plants that collectively provide 29.0% of the total power generation (GWh) in the country in 2020. These plants range in age from 4 to 40 years old. Four additional plants are under construction.

The Korean Institute for Nuclear Safety (KINS), the South Korean equivalent of the US NRC, has mandated that tracer gas inleakage testing per Reg Guide 1.197 be instituted in all operating nuclear power plants. In this paper we present inleakage data for six South Korean nuclear power plants. Testing occurred between 2012 and 2016.

The plants reported here all enter a filtered Pressurization Mode in the event of a nuclear accident. Measured Pressurization Mode inleakage values range from 0 m^3/min to approximately 102 m^3/ min (3,598 SCFM). In addition, inleakage values were also obtained for operation in an Isolation/Recirculation Mode. These values range from approximately 8 m^3/min (290 SCFM) to approximately 129 m^3/min (4,561 SCFM). All values represent upper 95% confidence interval values as required by Reg Guide 1.197.

These tests provide the first tracer gas inleakage data obtained from South Korean nuclear power plants.

INTRODUCTION

The Korea Institute of Nuclear Safety (KINS) functions as the nuclear regulatory body of South Korea. KINS has adopted the US NRC generic letter 2003-01 and the subsequent guidance provided in TSTF 448. As such, KINS has mandated inleakage testing of South Korean nuclear power plant control room envelopes as described in US NRC Regulatory Guide 1.197 [1]. The Regulatory Guide in turn, describes inleakage testing using the tracer gas techniques documented in ASTM Standard E741 "Standard Test Method for Determining Air Change Rate in a Single Zone by Means of a Tracer Dilution" [2].

In this paper we present inleakage data obtained using tracer gas techniques as described in Reg Guide 1.197 for six South Korean nuclear power plants. Testing occurred between 2012 and 2016.

SOUTH KOREAN NUCEAR POWER

The South Korean nuclear power industry formally began in 1956 with the establishment of the Division of Nuclear Power within the South Korean government. In 1978 the first nuclear power plant, Kori#1, launched commercial operation providing 587 Megawatts of output. Since then, the industry has grown to incorporate 24 operating units located at five sites within South Korea. Erecting multiple units at each site allows more efficient maintenance and lower costs, but does reduce grid efficiency.

Of the 24 operating plants, 21 are Pressurized Water Reactors (PWR) and 3 are Pressurized Heavy Water Reactors (PHWR). Currently these plants provide 29.0% of the total power generation (GWh) in the country.

The first plants were constructed from designs by Westinghouse (Kori 1-4 & Hanbit 1-2), the French CP1 (Hanul 1,2), or the Canadian CANDU-6 (Wolsong 1-4). In 1986, the Korea Nuclear Power Plant Construction Technology Independent Plan’s was established with the goal to achieve self-reliance in nuclear power plant construction technology. From this plan, the KSNP (Korean Standard Nuclear Power Plant) was developed based off of the Asea Brown Boveri-Combustion Engineering (ABB-CE) System 80 reactor design. In 2005, the KSNP was rebranded as the OPR-1000 (Optimized Power Reactor-

1,000 MW) to compete in the international market for nuclear power plant construction. Twelve operating nuclear power plants in South Korea were constructed from the KSNP / OPR-1000 design. The South Korean government led G-7 project (1992 to 2001) was established to apply the lessons learned from the OPR-1000 to develop the APR-1400 (Advanced Power Reactor-1,400 MW) with improved safety, stability, and economy of scale. The first power plant to complete construction using the APR-1400 design was Shin-Kori Unit 3 in 2016. The APR-1400 design is currently operating at Shin Kori Units 3,4 and Barakah Units 1,2 in the United Arab Emirates.

As of 2022, Four Korean-designed PWR plants are under construction in South Korea, Shin-Hanul Units 1,2 and Shin-Kori Units 5,6. In addition, two more Korean-designed plants are under construction in the United Arab Emirates, Barakah 3,4. All six plants are model APR-1400 designs.

South Korean plants currently exhibit an availability in excess of 90%. In addition, South Korean nuclear plants have repeatedly recorded the lowest rate of emergency shutdowns in the world, a record due in large part to a highly standardized design, currently the APR-1400, with corresponding standard operating procedures.

All plants were designed to conform to the requirements of GDC 19. Hence, each plant exhibits a defined Control Room Envelope (CRE) and each possesses a dedicated Control Room Envelope Emergency Ventilation System (CREEVS). In the event of a radiological emergency, all plants enter a filtered pressurization mode of operation. In the case of a toxic gas event, all plants enter a recirculation operating mode.

MEASURING BUILDING AIR FLOWS USING TRACER GASES

Tracer gas techniques have been used to measure the air infiltration and ventilation characteristics of buildings for over 50 years. Tracer gas techniques are successfully used in other areas of ventilation engineering and industrial hygiene to provide accurate characterization of HVAC performance under actual operating conditions [3, 4].

There are three principal tracer gas techniques for quantifying airflow rates within a structure; namely, the tracer concentration decay method, the constant injection method, and the constant concentration method. All three of these techniques are incorporated in ASTM Standard E741. Several of these tracer techniques can be used to measure induced airflow rates in buildings such as those created by a mechanical air handling system.

The tracer concentration decay method is a direct way of measuring the airflow into a test volume rate under ambient flow conditions by measuring the decay in tracer concentration as a function of time within the test volume.

The constant injection method is an indirect method; i.e., it measures the equilibrium tracer concentration within a ventilated area. This concentration can be related to the airflow rate if the tracer release rate is known.

The constant concentration method is also an indirect method. It measures the amount of tracer as a function of time required to maintain a constant concentration within a ventilated zone or zones. The quantity of tracer injected can be related to the airflow rate.

To interpret data resulting from tracer gas methods, one employs a mass balance of the tracer gas released within a volume under test. Assuming that the tracer gas mixes thoroughly within the test volume, the mass balance equation is,

$$V\, dC(t)/dt = S(t) - q(t)C(t) \tag{1}$$

where V is the test volume, C(t) is the tracer gas concentration (dimensionless), dC(t)/dt is the time derivative of concentration, q(t) is the volumetric airflow rate into the test volume, S(t) is the volumetric tracer gas injection rate, and t is time.

The air exchange or infiltration rate, A is given by $A(t) = q(t)/V$ where A is in air changes per hour (h^{-1} or ACH). In the simplest case, the value of A represents the flowrate of "dilution air" entering the volume during the test interval. Note that this "dilution air" can be actual outside fresh air or, more generally, it can be air whose origin is not within the test volume.

CONCENTRATION DECAY METHOD

The simplest tracer gas technique is the tracer concentration decay method. After an initial tracer injection into the test volume, there is no source of tracer gas, hence $S(t) = 0$ in equation (1), and assuming A is constant, a solution to equation (1) is;

$$C = C_0 \exp(-A \cdot t) \qquad (2)$$

This method requires only the measurement of relative tracer gas concentrations, as opposed to absolute concentrations, and the analysis required to determine A is straightforward. To obtain a value for A equation (2) is expressed as:

$$A = 1/t \ 1n (C_0/C) \qquad (3)$$

In use, equation (3) is often recast to the following form:

$$\ln C = 1n \ C_0 - A \cdot t \qquad (4)$$

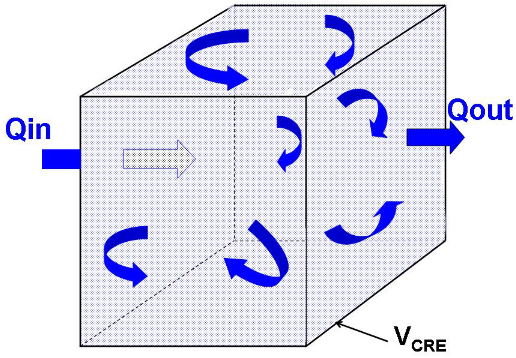
In practice one obtains a series of concentration versus time points and then performs regression analysis on the logarithm of concentration versus time to find the best straight line fit to the form of the equation given by equation (4). The slope of this straight line is A, the air exchange rate.

As depicted in Figure 1, the natural logarithm of the tracer concentration decreases linearly with time. The slope of this line is A, the air exchange rate. To calculate the air inleakage rate, one must have independent knowledge of the test volume from which,

$$q = A \cdot V \qquad (5)$$

The results obtained with this technique are exact only for a well-mixed volume, (i.e. concentration at a given time is the same throughout the test volume). Otherwise, the results will be subject to errors, with the magnitude of these errors depending on the extent of the departure from homogeneity.

1) Inject tracer and thoroughly mix in CRE



2) Measure Mean Concentration as function of time

Time (Hrs)	Mean Concentration
0.0	C0
0.5	C1
1.0	C2
1.5	C3
2.0	C4

3) Plot ln (concentration) vs. time and calculate slope by regression

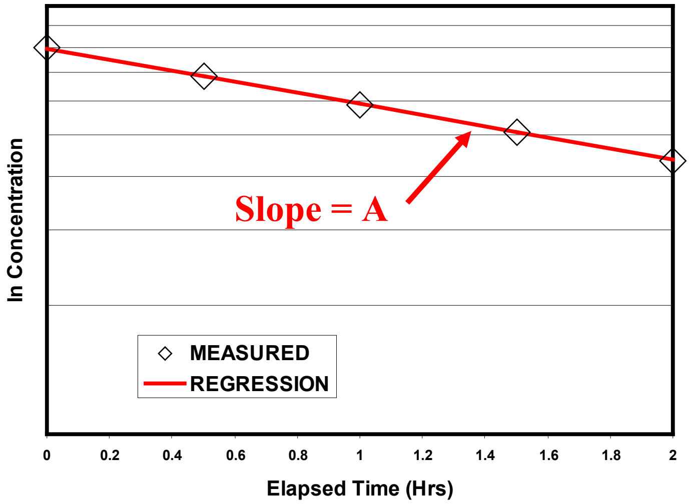


Figure 1 Tracer Concentration Decay Test

CONSTANT INJECTION METHOD

A companion tracer gas technique to the concentration decay method is referred to as the constant injection technique in which S(t) = constant. This technique is also known as the concentration buildup/steady state method. If A is also assumed to be constant, a solution to equation (1) is,

$$C(t) = (S/q) + (C_o - S/q) \exp(-A \cdot t) \qquad (6)$$

A schematic representation of a constant injection test along with a plot of equation (6) is provided in Figure 2.

As depicted in Figure 2, the tracer concentration initially increases with time but eventually reaches a constant value. After waiting a sufficient time (equal to at least 3/A), the transient dies out and concentration equilibrium occurs. Note that time equal to 3/A only provides 95% of concentration equilibrium. In practice waiting for time of 4/A provides concentration values at 98% of equilibrium. Equation (6) then becomes the simple constant injection equation,

$$C = S/q \qquad (7)$$

The results obtained with this technique are exact only when the system is in equilibrium, (i.e. concentration is not changing as a function of time) and the gas is well mixed throughout the test volume. Otherwise, the results will be subject to errors, with the magnitude of these errors depending on the extent of the departure from equilibrium.

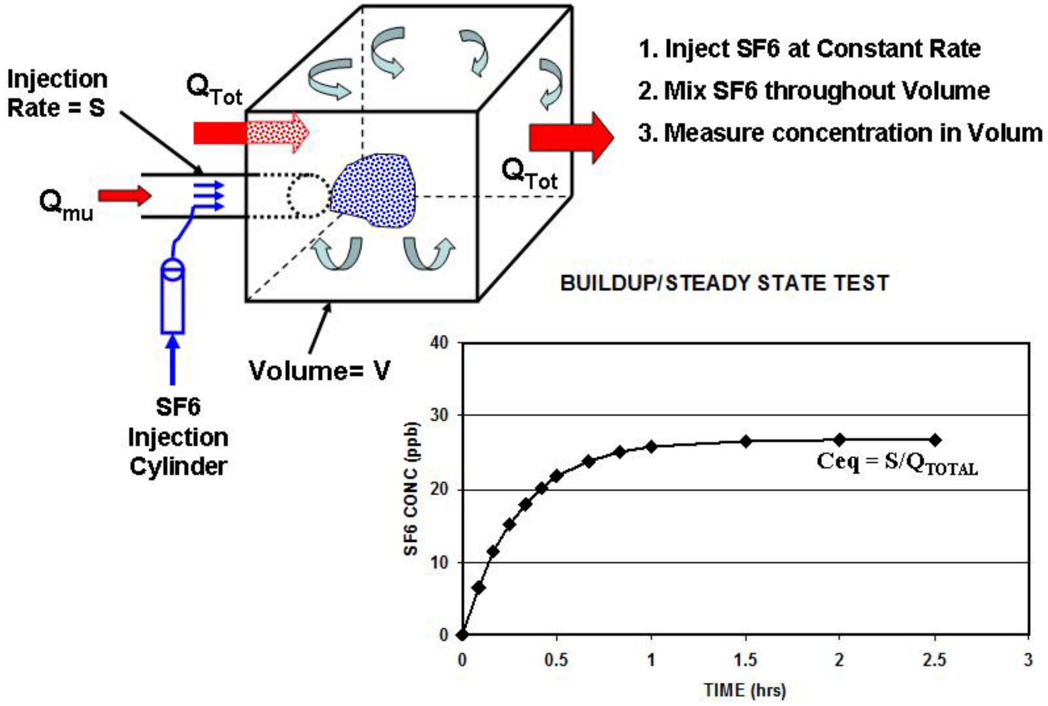


Figure 2. Concentration Buildup/Steady State Test

TRACER GAS FLOWRATE MEASUREMENT

For many years it has been known that a method to measure duct flowrates exists other than Pitot tube or hot wire anemometer traverses. This other method entails the use of a tracer gas dilution technique. This technique is a *volumetric* as opposed to a point measurement. Thus, knowledge of the internal cross-sectional area of the duct is not required.

To undertake such a measurement, a tracer gas is continuously metered into a flowing duct at a known rate. After allowing for mixing, air samples are collected at a number of points along a plane downstream of the injection point and the tracer gas concentration is measured. Assuming that the tracer gas is well mixed within the duct, the rate of flow is readily calculated from the ratio of the tracer injection flowrate to the diluted concentration (C_{av} - C_{us})--in symbols:

$$q = S / (C_{av} - C_{us}) \qquad (8)$$

In equation (8) C_{av} is the mean concentration downstream of the injection point, while C_{us} is the mean concentration of any tracer gas entering the duct upstream of the injection point. The equilibrium concentration in the duct is inversely proportional to the flowrate through the duct (as given by equation (8)). Thus, the measured concentration allows calculation of the flowrate since the injection flowrate is known. The basic test setup is shown in Figure 3. This method is codified as ASTM Standard E2029 “Standard Test Method for Volumetric and Mass Flow Rate Measurement using Tracer Gas Dilution” [5].

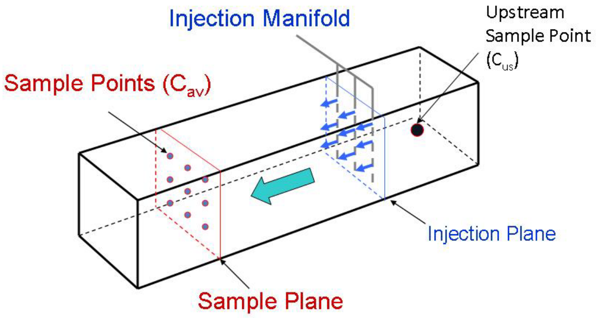


Figure 3. Schematic representation of tracer gas flowrate test.

This technique was used to measure makeup flowrate at the same time that the concentration buildup/steady state test was performed. Measuring makeup flow with a tracer gas technique rather than by means of a Pitot tube traverse results in a more accurate measurement of air inleakage into the CRE.

INLEAKAGE MEASUREMENT

In an air inleakage testing program using the concentration buildup/steady state technique, the total air inflow rate into the CRE is measured using equation (7). A constant flow rate of tracer gas is injected into the supply side of the CRE ventilation system and, after waiting for concentration equilibrium to occur, a number of measurements of the resulting concentration at the most downstream (in terms of negative differential pressure) portion of the CRE system are obtained. Recasting equation (7) yields the following:

$$q_{tot} = S / C_{av} \qquad (9)$$

Where q_{tot} now represents the total air inflow into the CRE. q_{tot} is made up of two components, namely, the amount of makeup air, $q_{m/u}$ and the amount of inleakage, q_{unfilt} .

C_{av} is the mean concentration measured after concentration equilibrium has been obtained. Often this value is taken as the mean concentration of tracer gas in the CREEVS return duct. In practice a number of concentration readings taken over a period of time are used to determine C_{av}.

Making use of these quantities, we can write an expression for the total air inflow to the CRE as;

$$q_{tot} = q_{m/u} + q_{inleak} \qquad (10)$$

Rearranging equation (10) to put the known quantities on the same side of the equation results in;

$$q_{inleak} = q_{tot} - q_{m/u} \qquad (11)$$

Since $q_{m/u}$ was measured independently by using a tracer flow measurement technique, it is possible to calculate the total air inleakage into the CRE using equation (11).

Note that inleakage past CRE boundaries, isolation dampers, air handling unit housings, and return ducts contributes to q_{tot}.

MEASUREMENT UNCERTAINTY

The total uncertainty of each air inleakage rate was calculated using the prescription provided in ANSI/ASME Standard PTC 19.1-1985 (Reaffirmed 1990) "Measurement Uncertainty" [6] and represents 95% confidence limits. Uncertainties for all derived and measured quantities are incorporated into the analysis.

In simplest terms, a 95 % confidence limit means that if a measurement were to be repeated 100 times, 95 times the resulting value would lie between the Lower and Upper Confidence Limit. Statistically all values between the Lower Confidence Limit (LCL) and Upper Confidence Limits (UCL) are valid data. If, however, the Confidence Limits are relatively large there is no guarantee that any given measured value will lie close to the mean value.

Mathematically the inleakage rate data in this paper are quantified as a value, q_{inleak}, plus or minus a 95% Confidence Limit (Urss). In symbols one obtains an inleakage value that lies between these extremes.

$$q_{inleak} - U_{rss} \leq = q_{inleak} \leq q_{inleak} + U_{rss} \qquad (12)$$

Note that Reg Guide 1.197 specifically requires that for inleakage values above 2.83 m^3/min (100 CFM) the upper 95% value must be reported and incorporated into any habitability analysis.

MEASURED DATA

The tracer gas inleakage measurements described in this paper were undertaken by a test crew consisting of staff members from the Korea Filter Testing Laboratory (KFTL) and Lagus Applied Technology, Inc. (LAT).

Testing of air samples for the presence of tracer gas was performed by means of several channels of electron-capture gas chromatograph (AUTOTRAC® Model 101) manufactured for field use by LAT. In order to ensure the greatest possible measurement accuracy from the chromatographs, the calibration of each channel of analyzer was checked during each test. A calibration check was performed by injecting a standard tracer gas mixture into each analyzer at intervals during the test to ensure that no significant analyzer drift had occurred.

Table 1 provides the CRE volumes of each plant tested. These six plants provide a representative sample of the CRE size of South Korean nuclear power plants.

Table 1

Plant Characteristics

Plant	CRE Volume Approximately [m^3] (ft^3)
A	6,000 (211,888)
B	8,000 (282,517)
C	15,000 (529,720)
D	14,000 (494,405)
E	7,000 (247,203)
F	7,000 (247,203)

For all six plants, make-up flowrates were measured using the tracer gas dilution technique described earlier in this paper. A summary of the measured flowrates for both the A & B trains for each plant are presented in Table 2 below.

Table 2

Measured Pressurization Air (Makeup) Airflow Rates
m^3/min
(ft^3/min)

Plant	A Makeup Flow	B Makeup Flow
A	114.9 ± 8.3 (4,060 ± 294)	112.1 ± 6.4 (3,961 ± 227)
B	9.5 ± 0.3 (334 ± 12)	9.8 ± 0.4 (346 ± 13)
C	116.8 ± 6.9 (4,126 ± 245)	130.5 ± 7.9 (4,610 ± 279)
D	103.2 ± 4.7 (3,646 ± 165)	117.8 ± 4.8 (4,161 ± 170)
E	85.9 ± 4.7 (3,036 ± 165)	90.7 ± 4.4 (3,205 ± 156)
F	91.2 ± 4.4 (3,222 ± 154)	87.2 ± 4.2 (3,082 ± 147)

For all six plants, pressurization mode inleakage tests were undertaken in each emergency pressurization operating mode. Inleakage data representing the upper 95% confidence interval for each measurement of pressurization mode are provided in Table 3. Note also that the zero inleakage values in this table do not imply that an actual value of zero was measured, but rather that the difference between total inflow (q_{tot}) and pressurization air flow (q_{mu}) is statistically indistinguishable from a zero value.

Table 3

Upper 95% Pressurization Mode Inleakage Values

m^3/min

(ft^3/min)

Plant	A Train	B Train
A	0 (0)	11.5 (405)
B	102 (3,598)	91.0 (3,215)
C	8.9 (317)	0 (0)
D	0 (0)	0 (0)
E	0 (0)	4.3 (154)
F	0 (0)	0 (0)

Recirculation mode inleakage tests were also undertaken in each emergency isolation/recirculation operating mode. Inleakage data representing the upper 95% confidence interval for each measurement of recirculation mode inleakage are provided in Table 4.

Table 4

Upper 95% Recirculation Mode Inleakage Values

m^3/min

(ft^3/min)

Plant	A Train	B Train
A	49.2 (1,739)	42.5 (1,502)
B	129 (4,561)	125 (4,412)
C	65.1 (1,858)	69.9 (2,469)
D	8.2 (290)	15.4 (546)
E	23.1 (817)	21.4 (755)
F	12.3 (433)	12.9 (456)

DIFFERENTIAL PRESSURE MEASUREMENTS

Differential pressure between the CRE and all surrounding rooms were obtained during each tracer gas air inleakage test in Table 5. Differential pressures were measured using a pair of sensitive digital barometers.

Table 5

Pressurization Mode Differential Pressure Values

Pa

(in.W.G.)

Plant	A Train		B Train	
	Range	Average	Range	Average
A	-2 ~ 2 (-0.008 ~ 0.008)	-0.2 (-0.001)	-4 ~ 1 (-0.016 ~ 0.004)	-1.7 (-0.007)
B	-30 ~ 23 (-0.118 ~ 0.094)	-4 (-0.016)	-37 ~ 79 (-0.147 ~ 0.318	0.05 (0.002)
C	-103 ~ 281 (-0.414 ~ 1.127)	39 (0.156)	-236 ~ 148 (-0.947 ~ 0.595)	12 (0.049)
D	72 ~ 185 (0.291 ~ 0.744)	140 (0.564)	23 ~ 218 (0.094 ~ 0.877)	149 (0.598)
E	-45 ~ 107 (-0.181 ~ 0.429)	42 (0.168)	-75 ~ 121 (-0.301 ~ 0.485)	43 (0.173)
F	-1 ~ 216 (-0.005 ~ 0.866)	102 (0.408)	-14 ~ 204 (-0.055 ~ 0.818)	92 (0.368)

In all cases the CRE was found to be strongly positive with respect to surrounding areas. This suggests that any measured inleakage was due to duct and AHU housing inleakage as opposed to transport across CRE Boundary walls.

CONCLUSIONS

This sequence of tracer gas inleakage testing of six Control Room Envelopes as described in Reg Guide 1.197, represent the first successful inleakage tests undertaken in Korea. Eventually all Korean nuclear power plants will be tested using these techniques.

As is apparent from Table 3, there is considerable variability in the measured values across the six plants. Interestingly enough, the newest plants (plants E and F) also exhibit the lowest inleakage values. This may be due in part to standardized design of the APR-1400 and the increased emphasis on CRE inleakage when new plants are now constructed.

All data compare favorably with inleakage data obtained from US plants and generally confirm that the GDC 19 design criterion for CRE habitability have been met for these six plants.

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