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Long Term Repeatability of Pressurization Mode Inleakage Tests

P. L. Lagus, K. R. Grot, J. W. Carlyle, P. J. Helly
Lagus Applied Technology, Inc.
Escondido, California

K. M. Fleming
NCS Corporation
Columbus, Ohio

ABSTRACT

U.S. nuclear power plants that have adopted TSTF 448 are committed to tracer gas inleakage testing. Regulatory Guide 1.197 provides guidance on 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".

Neither the ASTM Standard nor the Regulatory Guide addresses the question of the repeatability of tracer gas inleakage test results.

Tracer gas inleakage data with the Control Room Envelope Emergency Ventilation System (CREEVS) operating in a pressurization mode have been collected over a period in excess of 12 years for two nuclear power plants denoted Plant 1 and Plant 2.

The mean value of inleakage for six individual tests over three periods (2002, 2012, 2015) for Plant 1 was 1.32 m^3/min (47 SCFM) with a standard deviation of 21%. The mean value of inleakage for six individual tests over three periods (2001, 2009, 2016) for Plant 2 was 4.20 m^3/min (148 SCFM) with a standard deviation 17%.

For comparison, in a previous paper documenting repeatability of Concentration Decay tests undertaken on a Recirculation CREEVS, four distinct tests produced data exhibiting a standard deviation of the mean air inleakage rate of less than 3%.

INTRODUCTION

U.S. nuclear power plants that have adopted TSTF 448 [1] are committed to tracer gas inleakage testing. Regulatory Guide 1.197 [2] provides guidance on 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" [3].

Tracer gas techniques have been used to measure the air infiltration and ventilation characteristics of buildings for over 30 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 [4,5].

Neither the ASTM Standard nor the Regulatory Guide addresses the question of the repeatability of tracer gas inleakage test results. The repeatability of tracer gas inleakage tests for CREEVS that isolate and re-circulate under emergency conditions has been discussed in a previous technical paper [6]. No such discussion has been published regarding the repeatability of tracer gas inleakage tests for pressurization mode CREEVS.

Tracer gas inleakage data with the CREEVS operating in a pressurization mode have been collected over a period in excess of 12 years for two nuclear power plants denoted Plant 1 and Plant 2.

MEASURING BUILDING AIR FLOWS USING TRACER GASES

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 the most recent revision of ASTM Standard E741 "Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution".
In all three methods, a gaseous or vapor tracer is introduced into a test volume and the resulting concentration of tracer is measured as a function of time. Conservation of mass equations then allow one to deduce mass flow properties within the test volume.

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

$$V \ dC(t)/dt = S(t) - q(t)C(t) \qquad (1)$$

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 rate A= q(t)/V provides a measure of the volume normalized air inleakage rate.

With the CREEVS operating in a Pressurization Mode, air inleakage testing is often undertaken using a constant injection of tracer gas. This method measures the equilibrium tracer concentration within a ventilated area. This equilibrium concentration can be related to the air flow rate into the test volume if the tracer release rate is known. It is possible to solve equation (1) assuming a constant tracer gas injection flow.
For the constant injection technique S(t) = constant. If A is also assumed to be constant, a solution to equation (1) is,

$$C(t) = (S/q) + (C_0 - S/q) \exp(-A \cdot t) \qquad (2)$$

A schematic representation of this technique is provided in Figure 1.

As depicted in Figure 1, the tracer concentration initially increases with time but eventually reaches a plateau. After waiting a sufficient time (for this testing equal to approximately 4/A), the transient dies out and concentration equilibrium occurs. Equation (2) then becomes the simple constant injection equation,

$$C = S/q \qquad (3)$$

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). Otherwise, the results will be subject to errors, with the magnitude of these errors depending on the extent of the departure from equilibrium. All tracer concentration data used in the calculation of inleakage values for this testing were equilibrium values. Hence equation (3) could be applied.

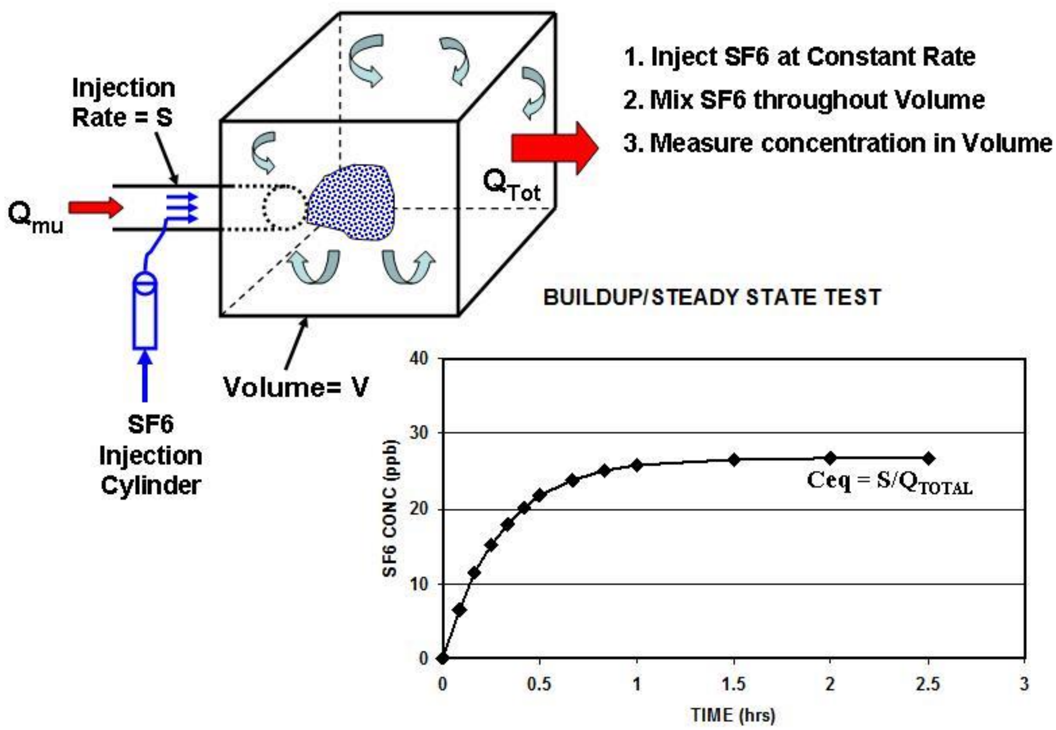

Figure 1. ASTM E741 Concentration Buildup/Steady State Test.

For Concentration Buildup/Steady State tests, the total air inflow rate into the Control Room Envelope (CRE) was measured using equation (3). A constant flow rate of tracer gas was injected into the pressurization air supply (makeup air) side of the respective CRE ventilation system and, after waiting for concentration equilibrium to occur, a number of measurements of the resulting concentration at the system return duct of the CREEVS were obtained. A number of samples were also obtained from throughout the CRE to demonstrate that good mixing of the tracer had been achieved within the CRE.

Recasting equation (3) yields the following:

$$q_{tot} = S / C_{av} \qquad (4)$$

Where q_{tot} now represents the total air inflow into either the CRE. q_{tot} is made up of two components, namely, the amount of makeup air, $q_{m/u}$ and the amount of air inleakage, q_{inleak} . C_{av} is the average concentration measured in the system return after concentration equilibrium has been obtained.

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

$$q_{tot} = q_{m/u} + q_{inleak} \qquad (5)$$

Rearranging equation (5) to put the known quantities on the same side of the equation results in;

$$q_{inleak} = q_{tot} - q_{m/u} \qquad (6)$$

For the testing at both plants $q_{m/u}$ was measured by a tracer gas technique based on ASTM Standard E2029 "Standard Test Method for Volumetric and Mass Flow Rate Measurement using Tracer Gas Dilution" [7] but is not described further in this paper.

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” [8] 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.

$$q_{inleak} - U_{rss} \leq q_{inleak} \leq q_{inleak} + U_{rss} \qquad (7)$$

INLEAKAGE DATA

For the purposes of air inleakage testing at Plant 1, the CRE consisted of the Main Control Room (MCR) and the ductwork and air handling units that comprise the CREEVS. The volume of the CRE is less than 850 m^3 (30,000 $Ft^{3)}$. The Mechanical Equipment Room (MER) lies outside the CRE and contains the entire CREEVS (A Train and B Train). It abuts the CRE, and is located on the same level as the CRE. It possesses a volume of less than 1/3 the CRE volume. Figure 2 provides a P&ID of the CREEVS.

A summary of the measured inleakage data encompassing six data sets over a 13 year span for Plant 1 is provided in Table I. The mean inleakage for the six tests was 1.33 m^3/min (47 SCFM) with a standard deviation of 0.27 m^3/min (10 SCFM). A plot of these data with the attendant uncertainties is provided in Figure 3. In this figure, the red diamonds represent the measured inleakage rates, while the black diamonds represent the upper and lower 95% confidence limits for each measurement. The upper and lower green lines represent one standard deviation above and below the mean value for the six measurements. The pressurization flow rates ranged from 6.43 to 7.42 m^3/min (227 to 262 SCFM).

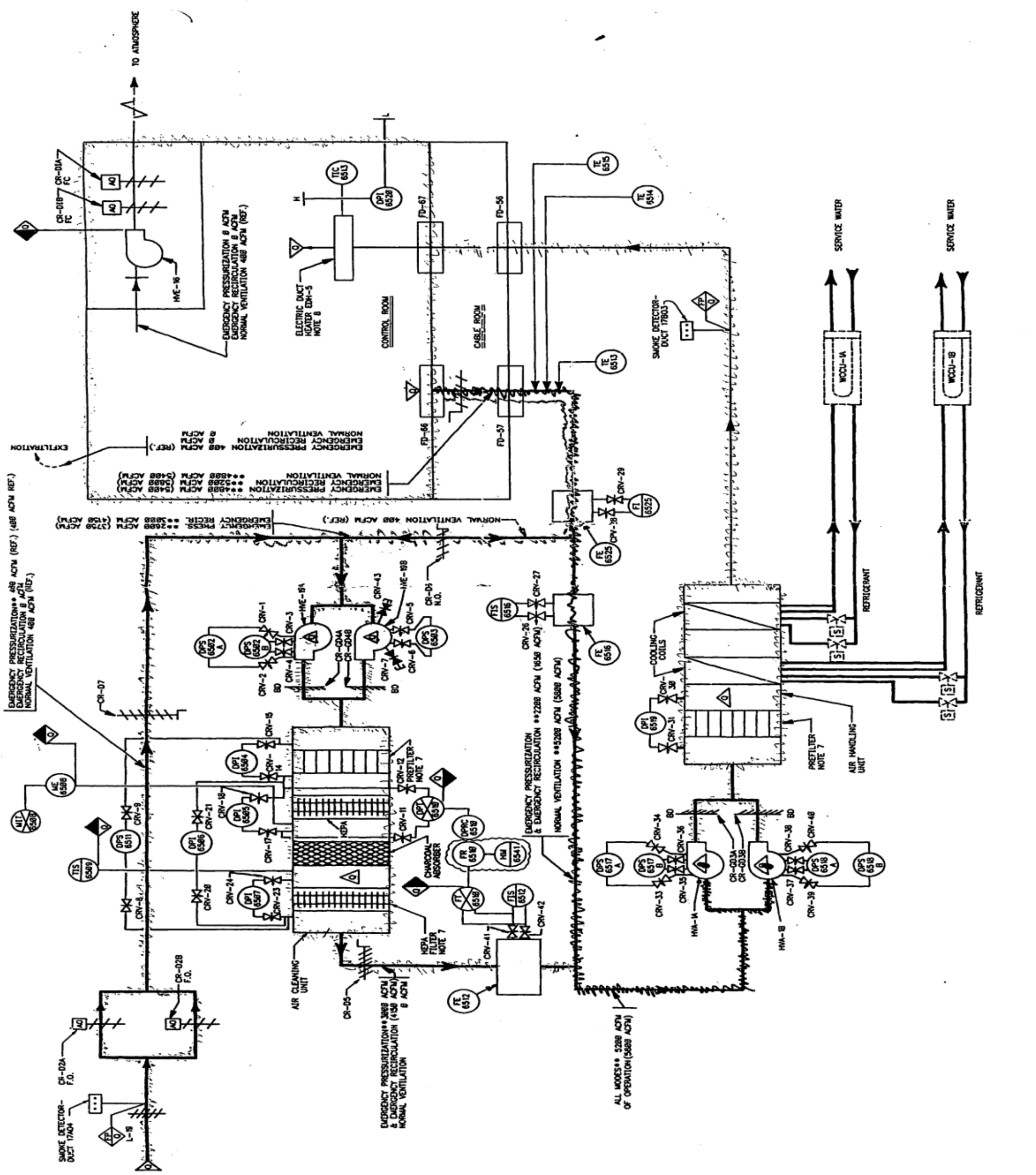

Figure 2. P&ID of Plant 1 CREEVS

Table I

Inleakage data in m^3/min for Plant 1

Year	2002		2012		2015	
Train	A	B	A	B	A	B
Inleakage	1.88	1.47	1.13	1.24	1.13	1.13
Urss (+/-)	0.42	0.23	0.51	0.11	0.28	0.11

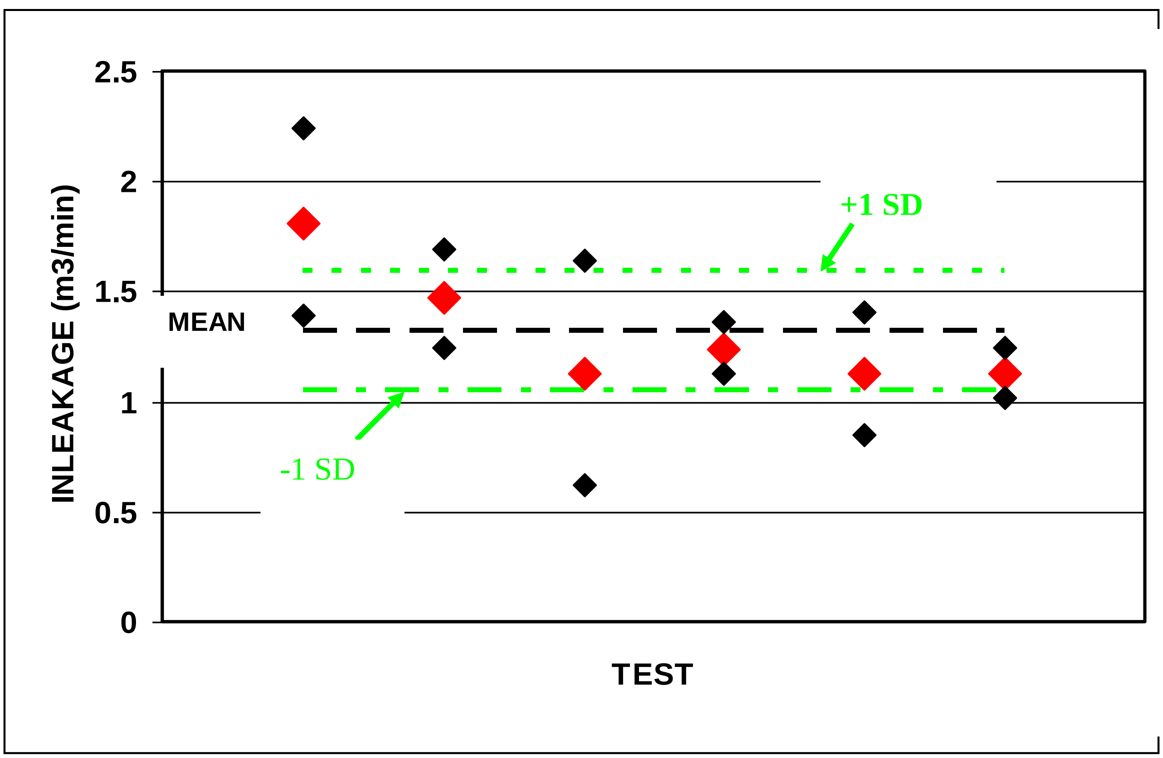

Figure 3. Inleakage data for Plant 1

For the purposes of air inleakage testing at Plant 2, the CRE consisted of the MCR and several support rooms within the controlled area as well as the associated CREEVS ductwork. The volume of the CRE is less than 2550 m^3 (90,000 Ft^3). Plant 2 has two distinct MERs housing respectively A Train or B Train both of which lie outside the CRE. The two MERs are located immediately above the MCR on the next higher level. Each MER possesses a volume of approximately 1/2 the CRE volume. Figure 4 provides a P&ID of the CREEVS.

A summary of the measured inleakage data encompassing six data sets over a 15 year span for Plant 2 is provided in Table II. For Plant 2 the mean inleakage was 4.20 m^3/min (148 SCFM) with a standard deviation of 0.73 m^3/min (26 SCFM). A plot of these data with the attendant uncertainties is provided in Figure 5. In this figure, the red diamonds represent the measured inleakage rates, while the black diamonds represent the upper and lower 95% confidence limits for each measurement. The upper and lower green lines represent one standard deviation above and below the mean value of the six measurements. The pressurization flow rates ranged from 18.9 to 22.5 m^3/min (669 to 794 SCFM).

Table II

Inleakage data in m^3/min for Plant 2

Year	2001		2009		2016	
Train	A	B	A	B	A	B
Inleak	5.55	3.87	4.38	3.45	3.96	3.96
Urss (+/-)	0.28	0.42	0.28	0.28	0.71	1.25

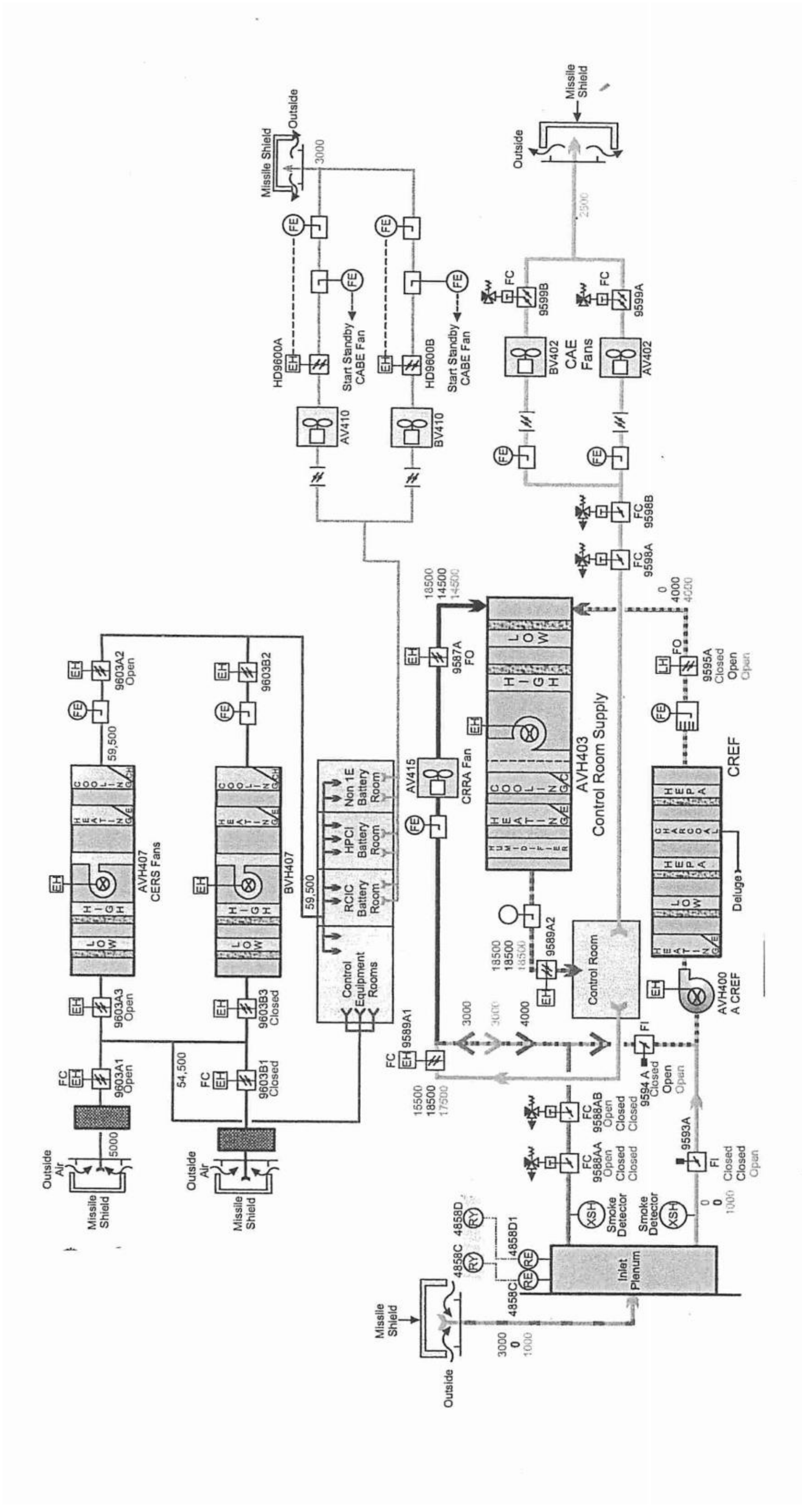

Figure 4. P&ID of Plant 2 CREEVS

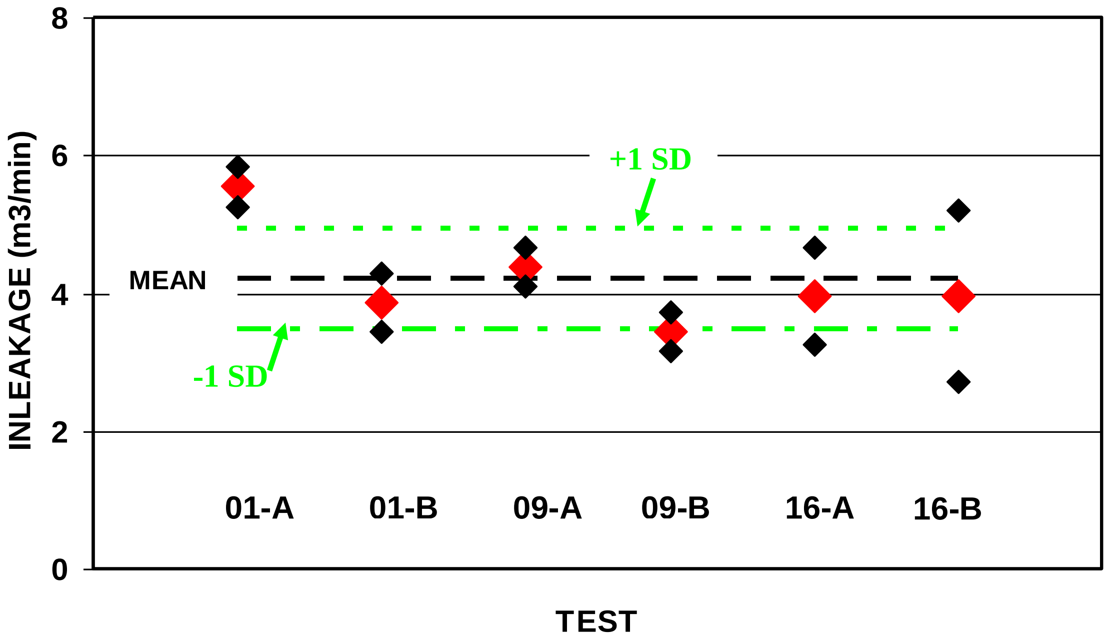

Figure 5. Inleakage data for Plant 2

For both plants the proximity of the respective MERs ensured that relatively short runs of CREEVS duct work were required to service the CRE. All duct work, air handling unit housings and filter housings incorporate welded seams. All control dampers and isolation dampers are butterfly type dampers.

DIFFERENTIAL PRESSURE MEASUREMENTS

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

In both Plant 1 and Plant 2, the CRE differential pressure with respect to all surrounding rooms was demonstrably positive for every one of the inleakage tests. Thus any measured inleakage was most likely due to the existence of inleakage paths in the individual CREEVS contained within the respective Mechanical Equipment Rooms.

CONCLUSIONS

The mean value of inleakage for six individual tests over three periods (2002, 2012, 2015) for Plant 1 was 1.88 m^3/min (47 SCFM) with a standard deviation of 21%. The mean value of inleakage for six individual test over three periods (2001, 2009, 2016) for Plant 2 was 5.55 m^3/min (148 SCFM) with a standard deviation 17%.

One should note that for both data sets, only the initial inleakage value exceeded the mean by more than one standard deviation. Since the test crew and the gas analysis equipment were identical for all data sets one might infer that the improvement from the first data sets was due to enhanced maintenance of the CRE Boundary and/or the CREEVS between the first and second round of inleakage testing

The magnitude of the standard deviation for these pressurization mode inleakage measurements reflect the fact that as the inleakage value becomes smaller, the relative uncertainty in any given measurement becomes larger due to the well known problem of differencing two numerical values which are close to each other in magnitude.

Assuming that substantially similar measurement and gas injection apparatus is used, the expected repeatability should be similar to the data reported in this paper. The use of different gas analysis and gas injection apparatus will necessarily result in different values of standard deviation and hence different overall repeatability of inleakage data sets.

Comparison of measured inleakage rates over an extended period of time relies not only on the constancy and repeatability of the testing technique, but due to the long period of time that elapsed, also relies on the fact that the CRE boundary and the CREEVS have been maintained so as to continue to function in an optimal manner. For both of these plants the CRE Boundary and CREEVS appear to have been satisfactorily maintained.

It should be noted that in the previously referenced technical paper the four distinct Recirculation Mode inleakage tests exhibiting a standard deviation of 3% were performed sequentially over a four day period.

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