Inleakage Re-testing in Light of TSTF 448

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Generic Letter 2003-01 required that all US nuclear power plants report the measured air inleakage value for each Control Room Envelope to confirm that assumptions utilized in the plant radiological habitability analysis were valid. A companion document, Regulatory Guide 1.197, provided test guidance and suggested that each CRE be retested at a six year interval.

In 2007, the US Nuclear Regulatory Commission published TSTF 448 in the Federal Register. Amongst many allowable plant and Tech Spec modifications, this document mandates a boundary control program for any plant that adopts the TSTF and further requires a CRE inleakage retest every six years.

This paper summarizes measured inleakage values for five Control Room Envelopes in plants that have undertaken one or more control room inleakage re-tests. Based on these measured values, it appears that, at least for these plants, the in-place boundary control program has maintained the leak integrity of the CRE boundary.

During 2009 and 2010, many US nuclear plants will retest their Control Room Envelopes. These preliminary results suggest that those plants with an *active* boundary control program will exhibit inleakage values that differ little from the previously measured values.

1.0 Tracer Gas Ventilation Measurements

Tracer gases 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 [1,2].

Within the nuclear power community, tracer gas techniques have been used since the early 1980's to measure airflow patterns, to investigate health and safety monitor locations, as well as to understand potential gaseous radioactive contaminant migration within selected buildings [3,4]. In the past few years tracer gas measurements designed to measure inleakage (either total or unfiltered) into a nuclear power plant control room have been accepted by the NRC and are often requested whenever questions arise regarding the performance or adequacy of nuclear power plant control room habitability systems.

Both Regulatory Guide 1.197 and Generic Letter 2003-01 explicitly assert that tracer gas testing is an acceptable method to characterize Control Room Envelope inleakage. In these documents, the NRC has denoted tracer gas testing as Integrated Inleakage Testing, since the test itself measures the overall inleakage into the CRE.

TSTF 448 (Revision 3) was adopted by the NRC in 2007. Amongst many allowable plant and Tech Spec modifications, this document mandates a boundary control program for any plant that adopts the TSTF and further requires a CRE inleakage test every six years.

2.0 Measuring Building Air Flows Using Tracer Gases

There are three principal tracer gas techniques for quantifying air flow rates within a structure; namely, the tracer concentration decay method, the constant injection or concentration buildup/steady state 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 Rate in a Single Zone by Means of a Tracer Gas Dilution"[5]. Several of these tracer techniques are used to measure induced air flow 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 air flow rate extant within a test volume under ambient flow conditions by measuring the decay in tracer concentration as a function of time within the space being tested.

The constant injection or concentration buildup/steady state method is an indirect method; i.e., it measures the equilibrium tracer concentration within a ventilated area. This concentration can be related to the air flow 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 air flow rate. At present this is primarily a research method since the equipment required is more complex than that required for either the concentration decay or the constant injection test.

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

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

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 (or out of) 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 flow rate 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.

2.1 Concentration Decay Air Inleakage Measurements

The simplest tracer gas technique is the tracer concentration decay test. After an initial tracer injection into a test volume S(t) is zero, and assuming A is constant, the solution to equation (1) for concentration as a function of time is given by:

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

where C_0 is the concentration at time t=0.

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. In use, equation (2) is often recast to the following form;

$$\ln C = 1\text{n}\, C_0 - A \cdot t \qquad (3)$$

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 (3). The slope of this straight line is A, the air exchange rate. The technique is shown schematically in Figure 1.

2.2 Constant Flowrate Tracer Gas Injection Air Inleakage Measurements

It is possible to solve equation (1) assuming a constant tracer gas injection. For the constant injection technique S(t) = constant. If A is also assumed to be constant, a solution to equation (1) is,

$$C(t) = (S/L) + (C_0 - S/L) \exp(-A \cdot t) \qquad (4)$$

A schematic representation of this technique is provided in Figure 2.

As depicted in Figure 2, the tracer concentration initially increases with time but eventually reaches a plateau. After waiting a sufficient time (equal to approximately 3/A as per ASTM E741), the transient dies out and concentration equilibrium occurs. Equation (4) then becomes the simple constant injection equation,

$$C = S/L \qquad (5)$$

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. Thus it is very important that all tracer concentration data used in the calculation of inleakage values are equilibrium values. Later in this paper this point is discussed further.

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 (5). 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 (5) yields the following:

$$L_{tot} = S / C_{av} \qquad (6)$$

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

C_{av} is the average concentration measured at the downstream sample point described above after concentration equilibrium has been achieved. 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;

$$L_{tot} = L_{m/u} + L_{unfilt} \qquad (7)$$

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

Rearranging equation (7) to put the known quantities on the same side of the equation results in;

$$L_{unfilt} = L_{tot} - L_{m/u} \qquad (8)$$

Since $L_{m/u}$ can be measured independently either by means of a Pitot tube or hot wire anemometer traverse or by using a tracer flow measurement technique, it is possible to calculate the total air inleakage into the CRE using equation (6). Often $L_{m/u}$ is measured using a tracer gas technique. ASTM Standard E-2029 provides useful guidance for performing tracer gas flow rate measurements [6].

3.0 Air Inleakage Measurements

Tables 1 and 2 present air inleakage values for five Control Room Envelopes that have been re-tested using tracer gas techniques (as of 1/1/08). The data have been separated into inleakage values for Pressurization CREVS and for Recirculation CREVS. Two columns are provided for operating mode data to accommodate plants that have the capability of operating different ventilation trains in the emergency mode. Note that plants B and C had no requirement to enter the Recirculation Mode, whereas plant E enters the Recirculation Mode in an emergency.

For some of the plants shown in the tables, retrofitting and remediation activities were undertaken after initial tracer gas testing in order to reduce the inleakage values.

Note that inleakage values measured for Pressurization Mode operation are presented in Standard Cubic Feet per Minute (SCFM), while inleakage values for Recirculation Mode operation are presented in Actual Cubic feet per Minute (ACFM). Note also that often a Recirculation Mode is labeled as an Isolation Mode.

3.1 Major Assumptions in the use of ASTM Standard E741

Three major assumptions in the use of ASTM Standard E741 are:

1) the CRE volume being tested acts as a single zone
2) the tracer gas is well mixed in the zone being tested
3) the tracer gas concentration has attained an *equilibrium* value
   (only necessary for a constant flow rate injection test)

Achieving satisfactory mixing of the tracer gas within the Main Control Room (MCR) has not been a problem in US nuclear plants as experience has shown that air flows into these well ventilated rooms are sufficient to mix tracer over the time interval that elapses prior to initiation of sampling.

For CRE's that encompass more than just the MCR, or for those CRE's that incorporate rooms that may not be as well ventilated as the MCR, mixing can be achieved by use of portable fans, high flow rate air blowers, or high flow rate blowers combined with lengths of flex duct (to direct air to poorly ventilated areas of the CRE).

By measuring the tracer concentration at spatially separated locations one can document the degree of mixing that has been attained. A common measure of the degree of mixing is the standard deviation of the mean of a number of spatially separated concentration measurements within the CRE. This is the value that is used in this paper. Experience has shown that mixing to within +/- 10 % is easily achievable in US plants and that often mixing to within +/- 2 % is possible. Table 3 presents concentration mixing data expressed as a percentage of the mean concentration for the CRE's in Tables 1 and 2.

In rare instances, usually due to the existence of numerous poorly ventilated rooms or multiple elevations within the CRE, adequate mixing may not be easily achieved. For these cases the CRE may not behave as a single zone unless extraordinary measures are taken to enhance mixing. While rare, the potential for this condition should be identified during review of plant ventilation drawings and the pre-test walk down.

For multi-room or multi-elevation Control Room Envelopes, identifying the potential for multi-zone behavior may be difficult, especially in cases where alternate ventilation equipment line-ups lead to entirely different ventilation patterns within the CRE. Enhanced deployment of additional mixing devices (portable fans, high flow rate air blowers, or high flow rate blowers combined with lengths of flex duct) as well as opening internal doorways and (possibly) stairwells may be required. Considerable effort may be necessary to ensure that proper tracer gas mixing can be achieved.

Even so, greater uncertainty in measurement may have to be tolerated since the CRE *must* behave as a single zone if the conditions for use of the E741 Standard are to be satisfied. Data averaging or other mathematical techniques that combine widely disparate concentration values only serve to mask actual mixing uncertainty and must not be used since these techniques create only an illusion that the CRE is behaving as a single zone.

Concentration equilibrium within a CRE is usually achieved by waiting an appropriate period of time after onset of tracer gas injection. ASTM E741 points out that waiting a time equal to 3/A (where A is the overall air exchange rate) results in a concentration value that is approximately 95% of the theoretical equilibrium concentration.

Note that for those CREs that require very low air inleakage values, attaining an apparent equilibrium concentration of only 95% of the true equilibrium value can result in the calculation of erroneous values for inleakage. This can be seen by referring to equations (6) and (8). A lesser value of C_{av} will result in a larger value of L_{tot} in equation (6) and hence to an overestimate of the actual inleakage calculated in equation (8). Thus, for conservatism, it is more appropriate to wait for 4/A or even 5/A equilibrium times. At some time point (usually lying between 4/A and 5/A) the measured value will lie within the measurement uncertainty of the particular gas analyzer used and the true equilibrium value. This point will define the equilibrium concentration so far as the measurement is concerned

It should also be noted that any significant *change* in the injection concentration of tracer gas or *any change* in the CRE makeup flow rate will require an additional period of time to equilibrate. If this time interval is not allowed to pass, erroneous values of total ventilation inflow (and ultimately inleakage) will be reported.

Technical reviews of inleakage measurement data by plant personnel must always include an evaluation of the adequacy of actual wait time when compared to minimum wait times required to achieve the desired theoretical equilibrium value, based on CRE volume and air exchange rate. Wait times that fail to meet the minimum recommended wait time described in ASTM E741 suggest that equilibrium was not achieved during the test and therefore, the data may be erroneous.

Table 4 provides percentage of the theoretical equilibrium value for the most common waiting times as well as actual wait time in hours for an assumed CRE volume of 150,000 Cu. Ft. and a total air inflow (makeup flow plus inleakage flow) of 1800 SCFM.

4.0 Habitability Assessment

For any plant that adopts TSTF-448, an active Control Room Habitability Program becomes a Tech Spec requirement. The Federal Register notice of TSTF-448 Revision 3 emphasizes that five major elements must be included in an acceptable Habitability Program Tech Spec:

1) **Definitions of the CRE and CRE boundary**

   These provide an accurate description of the areas within the CRE as well as the interfaces that form the CRE boundary. These definitions preclude ambiguity in the implementation of the CRH Program.

2) **Configuration Control and preventive maintenance of the CRE boundary**

   This item is included to ensure that the CRE boundary is maintained in its design condition.

3) **Assessment of CRE habitability at the frequencies stated in Reg Guide 1.197along with measurement of unfiltered inleakage into the CRE in accordance with the methods and at frequencies provided in Reg Guide 1.197**

   This element will ensure that CRE habitability is assessed in a manner consistent with pertinent section of Reg Guide 1.197.

4) **Measurement of CRE pressure with respect to all areas adjacent to the CRE boundary at designated locations for use in assessing the CRE boundary at a frequency of 18 month on a staggered basis (with respect to CREVs trains)**

   This item is included to ensure the CRE differential pressure is measured on a regular basis to identify changes that may warrant evaluation of the CRE boundary condition.

5) **Quantitative limits on unfiltered inleakage**

   This element establishes the measured unfiltered inleakage rate as the limiting value used in occupant radiological consequence analysis of design basis accidents.

The NEI Control Room Habitability Guide provides an excellent starting point for any plant specific CRE Habitability program [7]. An additional document to assist in establishing and maintaining a CRH Program has recently been prepared by NHUG, the Nuclear HVAC Utility Group [8].

5.0 Conclusions

Based on the measured values presented in Tables 1 and 2, it appears that the in-place boundary control program has maintained the leak integrity of the CRE boundary for the five CRE’s tested.

During 2009 and 2010, many of the US nuclear plants will retest their Control Room Envelopes. These preliminary results suggest that those plants with an *active* boundary control program will exhibit inleakage values that differ little from the previously measured values.

7.0 Acknowledgements

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8.0 References

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Table 1.

Measured Air Inleakage Values
(Pressurization Emergency Mode)

CRE	CRE Volume (Cu Ft)	Pressurization Mode Inleakage* Train A (SCFM)	Pressurization Mode Inleakage* Train B (SCFM)	Year of Test
A	184,000	222 +/- 55	88	1997
A	184,000	71	56	2006
B	108,000	80	128 Estimated	1998
B	108,000	0	0	2001
B	108,000	0	0	2007
C	54,000	73	236 Estimated	1998
C	54,000	0	0	2001
C	54,000	0	34	2007
D	141,800	45	-----	1994
D	141,800	64	-----	2004

* Note that per Regulatory Guide 1.197 Section 1.4, Inleakage rates below 100 CFM do not require uncertainty value.

** NM-Not Measured

Table 2.

Measured Air Inleakage Values
(Recirculation Emergency Modes)

CRE	CRE Volume (Cu Ft)	Recirculation Mode Inleakage Train A (ACFM)	Recirculation Mode Inleakage Train B (ACFM)	Year of Test
A	184,000	--	NM**	1997
A	184,000	--	469 +/- 26	2006
D	141,800	--	142 +/- 12	1994
D	141,800	--	222 +/- 30	2004
E	364,922	439 +/- 21	442 +/- 23	1997
E	364,992	450 +/- 19	501 +/- 26	1999
E	364,992	583 +/- 32	550 +/- 35	2007

** NM-Not Measured

Table 3

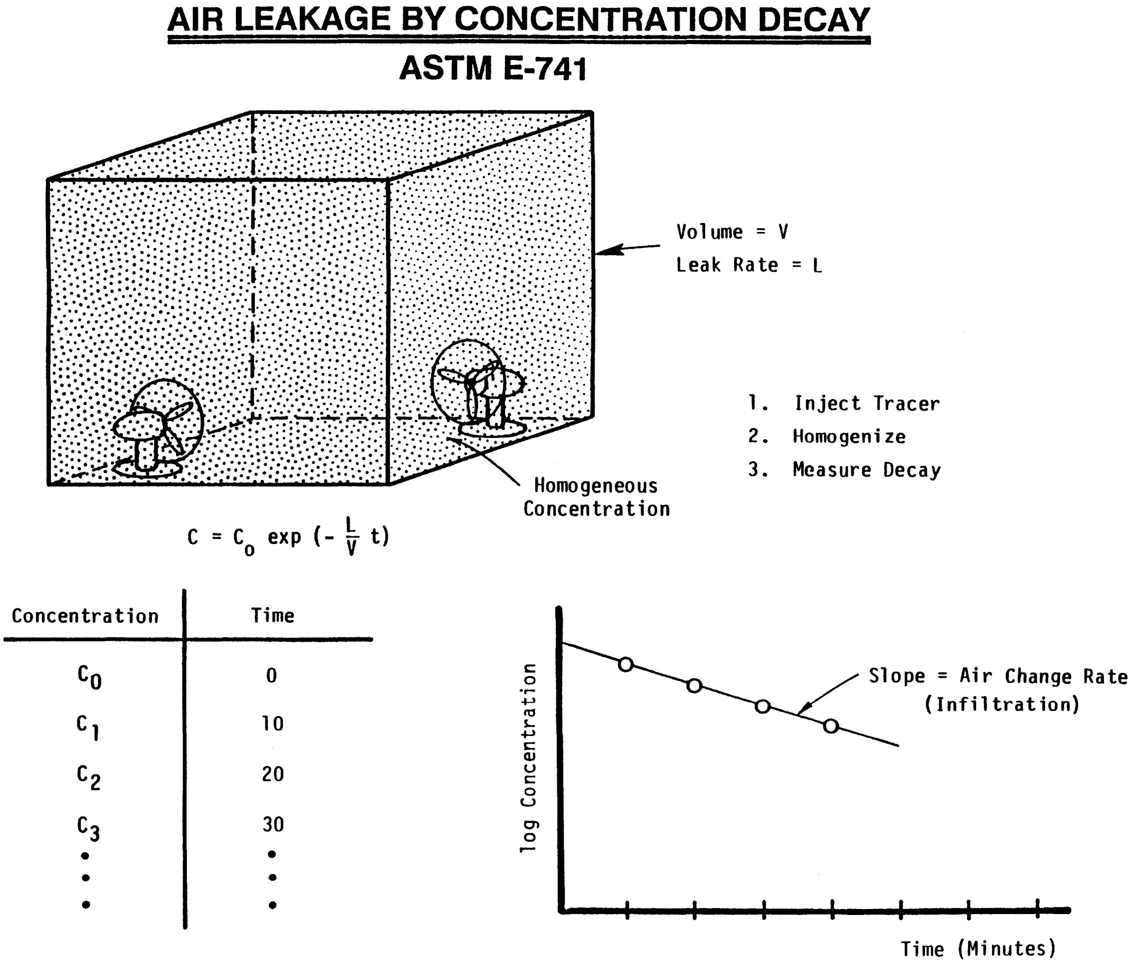
Tracer Gas Concentration Mixing for CREs in Tables 1 and 2

CRE	CRE Volume (Cu Ft)	Year	Maximum SD (% of Mean Concentration)
A	184,000	1997	2.4
A	184,000	2006	1.5
B	108,000	1998	1.4
B	108,000	2001	0.9
B	108,000	2007	1.5
C	54,000	1998	1.8
C	54,000	2001	0.9
C	54,000	2007	1.2
D	141,800	1994	1.6
D	141,800	2004	4.1
E	364,922	1997	4.2
E	364,992	1999	6.5
E	364,992	2007	4.6

Table 4

Times to and Percentage of Equilibrium for Constant Injection Test
(CRE Volume of 150,000 Cubic Feet, Inflow Rate of 1800 CFM)

Waiting Time	Time in Hours	% of Equilibrium
3/A	4.17	95
4/A	5.57	98.2
5/A	6.93	99.3



$$C = C_0 \exp\left(-\frac{L}{V} t\right)$$

Concentration	Time
C_0	0
C_1	10
C_2	20
C_3	30
•	•
•	•
•	•

Figure 1. Concentration Decay Test

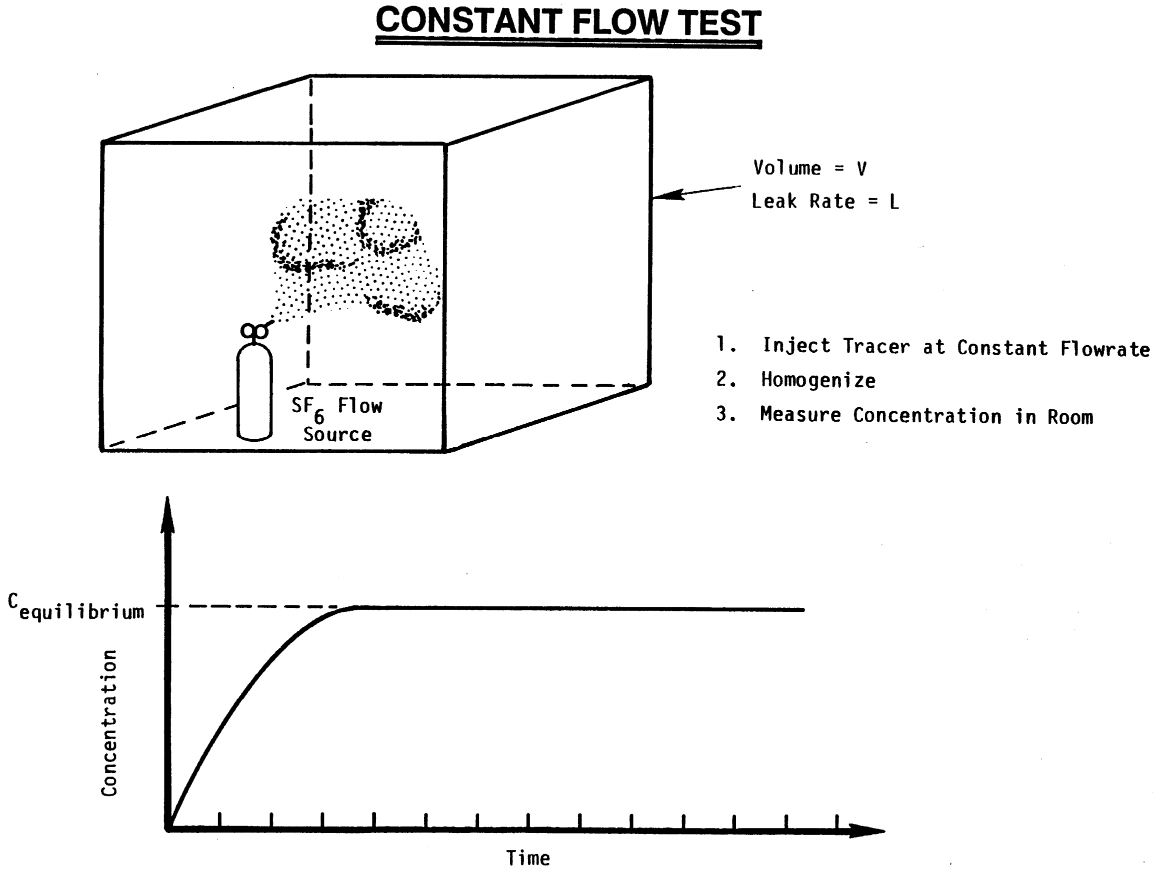


Figure 2. Concentration Buildup/Steady State Test