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Control Room Inleakage Measurements using Tracer Gas Techniques

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As early as 1984, inleakage measurements were undertaken for control rooms and other structures associated with the chemical process industry. The driving force for these measurements was the need to locate so called “Temporary Safe Havens” within the plant environment. These Safe Havens are intended to provide a habitable environment for the plant personnel during a toxic release.

In 2003, the United States Nuclear Regulatory Commission requested data on the inleakage characteristics of all operating nuclear power plants in the US. Essentially this request required all operating plants to measure the inleakage into the control room.

In both the chemical process industry and the nuclear power generation industry, inleakage testing has been undertaken using tracer gas techniques that are based on ASTM Standard E 741 ” Standard Test Method for Determining Air Change Rate in a Single Zone by Means of a Tracer Dilution”.

In the chemical process industries, the predominant response to emergency conditions is to isolate the control room and place the ventilation system into a recirculation mode. This creates a so called “neutral pressure condition” in the control room. Ideally the control room is neither pressurized nor de-pressurized when operated in this condition.

Within the nuclear power industry, the majority of control rooms respond to a radiation emergency by pressurizing the control room with filtered outside air. A lesser fraction of these control rooms isolate and operate in a recirculation mode in the manner of the chemical process industry. For a chemical release emergency most nuclear power plant control rooms isolate and operate in a recirculation mode in the same manner as the chemical process industry.

In this paper, we provide a description of the techniques used to measure inleakage for both neutral pressure and pressurized control rooms. In addition, some of the measured inleakage data for both control room types will be presented to illustrate the range of inleakage values that have been found in actual practice. The safety significance of these measured values will also be discussed.

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].

Inleakage, as we have used it in this paper, is defined as the unwanted infiltration of potentially contaminated air into a control room environment when the emergency ventilation system is operating in response to a hazardous release (chemical, radiological or biological) outside the control room boundary. Note that air leakage past control room boundaries, air handling unit housings, isolation dampers, and return ducts contributes to inleakage.

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 into a nuclear power plant control room have been required by the USNRC [5,6]. Inleakage tests using tracer gas techniques have been performed in almost all of the operating plants in the United States [7,8].

Within the petrochemical industry, safe haven testing is routinely performed using tracer gas techniques, but this author could find little published data in the literature. A single publication [9] provides some data for the chemical process industry control rooms.

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"[10]. 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 the constant concentration method 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,

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

where V is the test volume, C(t) is the tracer gas concentration (dimensionless), dC(t)/dt is the time derivative of concentration, L(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) = L(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.

Recall that the simplest tracer gas technique is the tracer concentration decay test. After an initial tracer injection into a test volume S(t) in equation (1) is zero. 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;

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

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.

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 this figure, the tracer concentration initially increases with time but eventually reaches a plateau. After waiting a sufficient time (equal to at least 3/A but preferably longer), the exponential term 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 using this method are equilibrium values.

In an air inleakage testing program using this concentration buildup/steady state technique, the total air inflow rate into the control room is measured using equation (5). A constant flow rate of tracer gas is injected into the supply side of the emergency ventilation system. One then waits for concentration equilibrium to occur. Upon attaining an equilibrium condition a number of measurements of the resulting concentration within the control room or at the most downstream (in terms of negative differential pressure) portion of the emergency ventilation 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 control room. L_{tot} is made up of two components, namely, the amount of makeup air (i.e. outside air provided to slightly positively pressurize the control room), $L_{m/u}$ and the amount of inleakage, L_{inleak} .

C_{av} is the average concentration measured within the control room or the downstream point after concentration equilibrium has been obtained. 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 control room as;

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

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

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

Since $L_{m/u}$ can be measured independently, it is possible to calculate the total air inleakage into the control room using equation (8). Often $L_{m/u}$ is measured using a tracer gas technique. ASTM Standard E-2029 “Standard Test Method for Volumetric and Mass Flow Rate Measurement in a Duct Using Tracer Gas Dilution” provides useful guidance for performing tracer gas flow rate measurements [11].

For those control rooms that utilize a very low makeup flow rate with a correspondingly low air exchange rate, the time to concentration equilibrium can be unreasonably long. This presents a severe experimental challenge to undertaking an air inleakage test since it is difficult to maintain reasonable experimental conditions over extended periods in operating control rooms.

Table 1 provides a summary of times required for the exponential term in equation (4) to decay to a negligible value in a concentration buildup/steady state inleakage test in an example low makeup flow rate situation. In this table the column denoted “% of Equilibrium” denotes how good an approximation the use of equation (5) represents. Waiting a very long time (infinite!) would result in the value of the exponential in equation (4) becoming identically zero. The value of the “% of Equilibrium” column would become 100% and equation (5) would be exactly satisfied. In practical terms equilibrium times between 4/A and 5/A represent a reasonable experimental limits based on analyzer calibration and analyzer repeatability although ASTM E741 allows a wait time of 3/A to achieve equilibrium.

For plants that incorporate a low makeup flow rate pressurization emergency ventilation system, a tracer gas technique called the makeup flowrate/concentration decay test is often used to measure inleakage [12]. This technique also is based on the use of ASTM Standard E741 in conjunction with ASTM Standard E2029.

In this test method, tracer gas is continuously injected into the makeup air stream of the emergency ventilation system at a constant rate while the makeup flow rate is measured. Tracer gas is then injected (usually at a higher flow rate or a higher injection concentration) into the control room for an additional period of time in order to achieve a concentration of 20 to 30 parts per billion. Upon attaining a concentration value in this range tracer gas injection is stopped and the gas is allowed to disperse throughout the control room.

After waiting for adequate mixing to occur, timed sampling for tracer gas is initiated. From these samples one obtains a series of concentration versus time points and performs regression analysis on the logarithm of concentration versus time to find the best straight-line fit to the data. The slope of this straight line is the volume normalized air inleakage rate in air changes per hour (ACH). Knowledge of the control room volume allows calculation of the total air inflow rate in appropriate units.

Makeup flow rates are measured by a tracer gas dilution technique (ASTM E2029) before and after measurement of the total air inflow. The values are averaged to obtain the mean makeup flow rate extant during the testing. Knowledge of the makeup flow rate in combination with a measured total air inflow value allows calculation of the amount of air provided to the control room (i.e. inleakage) that is not provided by makeup flow by differencing these two measured values.

3.0 Air Inleakage Measurements: Nuclear Power Plants

In Tables 2 and 3 we present a selection of air inleakage values for nuclear power plant control rooms. The volume of the control rooms ranged from roughly 550 m^3 to approximately 11,000 m^3. The data have been separated into inleakage values for Pressurization Systems and for Recirculation Systems. Nearly 80% of existing nuclear power plants enter a filtered air pressurization mode during a radiological emergency while 20% of the plants enter a filtered recirculation mode. During a toxic gas emergency nuclear plants enter a recirculation mode.

The electronegative gas, sulfur hexafluoride (SF6), was used as a tracer in the all tests. This gas is generally recognized as non-toxic and non-reactive. Since it is easily detectable in minute quantities by means of electron capture gas chromatography, SF6 is an ideal tracer gas for ventilation system performance investigations.

For the tests tabulated in Tables 2 and 3 all tracer gas measurements were performed by means of chromatographic instrumentation manufactured for field use. On site calibration using certified calibration standards was performed daily prior to initiation of each test to ensure that instrument drift and any sensitivity variations would be minimized. Analytical sensitivity to SF6 ranged from 500 parts per trillion to approximately 50 parts per billion.

Air samples were obtained using disposable polypropylene syringes. Within the control rooms air samples were taken directly as grab samples. Air samples from a number of locations within ductwork were obtained using pump/manifold sampling systems.

A major assumption in the use of ASTM Standard E741 is that in the zone being tested the tracer gas is well mixed. Achieving satisfactory mixing of the tracer gas within the vast majority of control rooms has not been a problem. Most nuclear power plant control rooms are well ventilated and the ventilation flows are sufficient to mix tracer over a time interval on the order of ½ to 2 hours.

A small percentage of control rooms incorporate additional rooms that may not be as well ventilated as the others. For these additional rooms adequate tracer gas mixing can be achieved by using portable oscillating fans. By measuring the tracer concentration at spatially separated locations one can then document the degree of mixing that has been attained. Experience has shown that mixing (Relative Standard Deviation of Control Room Concentration) to within +/- 10 % is easily achieved and that often mixing to within +/- 2 % is possible.

A major source of uncertainty in the data of Table 3 for Recirculation systems is incomplete knowledge of the volume of the control room. In any measurement of inleakage for a Recirculation system, the uncertainty in control room volume is directly proportional to the uncertainty in the calculated inleakage.

4.0 Air Inleakage Measurements: Chemical Process Plants.

Comparatively little has been published regarding inleakage into Chemical Process Plant Control Rooms or adjacent Safe Haven areas. Traditionally, in response to an inadvertent chemical release these control rooms either i) isolate and enter a recirculation mode, or ii) isolate and secure the control room HVAC system(s).

The only published study of which this author is aware provided air exchange rates for a number of control rooms within a Chemical Process Plant complex [9]. The volume of these control rooms ranged from roughly 200 m^3 to approximately 3500 m^3. The measured inleakage data are provided in Table 4. Unfortunately no uncertainty estimates are provided for these data, but one can assume that the measurement uncertainties are comparable to those found for measurements in nuclear power plant control rooms.

5.0 Sources of Inleakage.

Inleakage is driven by adverse differential pressure relationships that may exist between the interior of the control room and i) the surrounding environment (adjacent rooms or outdoor areas), ii) the negative differential pressure portions of the emergency ventilation system including ductwork, iii) any positive differential pressure sections of non-emergency ventilation system ductwork that traverse the control room.

A summary of nuclear power industry experience for sources of inleakage is provided in Table 5. The inleakage sources are further categorized as “Frequent” or “Infrequent” subjectively based on the number of control rooms in which the listed item contributed to significant inleakage. A more comprehensive list is provided in a recent publication dealing with control room habitability in the nuclear power industry [13]. Based on this author’s experience a similar list can be created for chemical process plant control rooms.

6.0 Reproducibility of Inleakage Measurements.

Since performing an inleakage measurement can be a time consuming and relatively expensive undertaking, repeated inleakage measurements under the same operating conditions seldom have been undertaken. Thus to obtain an estimate of the uncertainty in the measurement it is necessary to rely on confidence interval calculations such as ANSI/ASME Standard PTC 19.1 “Measurement Uncertainty: Instruments and Apparatus” [14].

The major reason to assess inleakage uncertainty using a confidence interval approach is that usually only a small number of measurements are performed in an operating nuclear power plant or chemical process plant. Due to cost and operational considerations it is not generally feasible to undertake a large enough number of essentially identical tests to generate numerical data that can be subjected to normal statistical analysis. Thus an uncertainty estimate based *solely* on the calculation of standard deviation does *not* represent a statistically valid approach to estimating the uncertainty in the data set.

The confidence interval approach attempts to combine systematic and random measurement uncertainties in a statistically valid manner. Essentially a confidence interval is a statistical estimate (based on a single series of measurements) of the spread expected in a series of repeated measurements. The confidence interval is usually given at some percentage of confidence-usually 95 %. Thus if we say the mean value of a measurement is K with a 95 % confidence interval of M, we imply that if we repeat the measurement 100 times, at least 95 times the measured value will lie between (K+M) and (K-M).

Confidence interval calculations, by their very nature, are conservative and rely on detailed knowledge of the uncertainties of the experimental apparatus and materials used to generate the data.

Mathematically the confidence interval is described by the following equation (9):

$$U_{95} = \pm\left[\sum_i B_i^2 + \sum \left(t_i \bullet S_i\right)^2\right]^{1/2} \qquad (9)$$

where

B_i =Systematic Uncertainties in Measurement Apparatus (Bias)
S_i =Random Uncertainties in Measured data (Standard Deviation)
t_i = Student’s “t” distribution value

This equation combines the systematic (or bias) uncertainties with the random (or measurement) uncertainties in a statistically defensible manner. Note also that the random uncertainties are augmented by a t value (the aptly named Student’s t statistic) that corrects for the fact the standard deviation of a small sample of data may not represent the value that would be obtained by a much larger sample.

Sources of systematic error include analyzer calibration gas uncertainty, analyzer response uncertainty, injection gas concentration uncertainty (when using a diluted concentration of tracer gas as the tracer source), and injection flow rate measurement uncertainty.

Sources of random uncertainty include makeup flow rate uncertainty, total air inflow uncertainty, analyzer concentration output uncertainty, and control room volume uncertainty.

The confidence intervals calculated for the measured inleakage values provided in Table 2 range from approximately 5 % to in excess of 100 % and average approximately 30 %. The confidence intervals for the nuclear power plant Recirculation systems shown in Table 3 are generally lower with a mean of less than 10%.

We should note that the uncertainty in the inleakage values determined for Pressurization systems will usually be greater than for Recirculation systems since in the former we are attempting to measure the difference between two relatively large numbers that are comparable in magnitude.

7.0 Safety Significance

Prior to obtaining a license to operate in the United States a nuclear power plant is required by law [15] to demonstrate that the control room environment will remain safe for operators in the event of a nuclear or chemical emergency. An extensive technical/regulatory literature exists [16,17] that allows evaluation of the likely exposure histories within the control room during a postulated nuclear emergency. The value of inleakage is a critical input parameter in any such safety analysis.

Prior to the use of tracer gas techniques, a variety of calculational and pressurization techniques were used in an attempt to estimate the amount of inleakage into a nuclear power plant control room. The resulting values for inleakage were of dubious technical merit and lacked any real physical basis for their use in subsequent habitability analyses. The most that can be said is that the majority of values so determined were usually conservative in terms of their safety significance.

Within the chemical process industry there is no regulatory requirement to measure control room inleakage. Nevertheless, recognized calculational techniques exist [18] for estimating the outdoor concentration, extent, and duration of a variety of chemical process accident-induced plumes. This plume concentration information may be used in conjunction with the measured values of inleakage to estimate the potential peak and mean concentrations as well as exposure times within an operating control room during a chemical emergency. Such information should be invaluable to emergency response planning personnel.

8.0 Conclusions

Inleakage into a control room of potentially contaminated air during accidental (or deliberate) external releases of hazardous materials can represent a major health and safety issue for operators of both nuclear power plants and chemical process plants.

In the past, control room designers and operators relied on a variety of engineering models in order to arrive at a value for air inleakage. These engineering models are based on crude and often incomplete assumptions about the nature of airflow through indoor spaces. However, as we have demonstrated in this paper, inleakage can be measured by recognized experimental methods. Such measurements allow the quantitative evaluation of the ability of control room emergency ventilation systems to mitigate the effects of external releases of hazardous contaminants.

In this paper we have provided a description of measurement techniques that have been used to measure control room inleakage values. Also provided are summaries of measured data from actual operating control rooms in both the nuclear power and the chemical process industries.

In the case of the nuclear power industry substantial effort has been expended over the last 10 years to minimize or eliminate inleakage as a safety concern.

In select sectors of the chemical process industry substantial effort has been expended toward the measurement of inleakage characteristics of operating control rooms to ensure the safety of operating personnel. Unfortunately few of these measurements have been published.

It is this author’s hope that when the next Vent Conference occurs (Vent 2008?) a substantially greater body of published data on inleakage of control rooms from other industries will be presented.

9.0 References

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Table 1

Times to Equilibrium in Equation (4) for A=0.24 ACH

(Control Room Volume of 4250 m^3, Makeup Flow Rate of 0.283 m^3/sec)

Value of t in Exponential	Time in Hours	% of Equilibrium
3/A	12.5	95
4/A	16.7	98.2
5/A	20.8	99.3

Table 2

Nuclear Power Plant
Pressurization System Inleakage Values

Plant	Inleakage (m3/sec)
A	0.0354 +/- 0.0118
B	0.0165 +/- 0.0208
C	0.0231 +/- 0.0231
D	0.0212 +/- 0.0123
E	1.91 +/- 0.38
F	0.0179 +/- 0.0061
G	0.0925 +/- 0044
H	0.512 +/- 0.0467
I	1.37 +/- 0.13
J	0.185 +/- 0.0675
K	0+/- 0.0142
L	0+/- 0.0198
M	0+/- 0.0245
N	0.129 +/- 0.0467
O	0.110 +/- 0.0609
P	0.0392 +/- 0.0175
Q	0.160 +/- 0.0340
R	0.416 +/- 0.0684
S	0.0071 +/- 0.0307
T	0.0415 +/- 0.0156
U	0.0363 +/- 0.0061
V	0.0571 +/- 0.0123
W	0.017 +/- 0.0052
X	0.0307 +/- 0.0411

Table 3

Nuclear Power Plant Recirculation System Inleakage Values

Plant	Inleakage (ACH)	Inleakage (m3/sec)
AA	0.0824	0.246 +/- 0.0071
BB	0.0382	0.121 +/- 0.0071
CC	0.0139	0.028 +/- 0.0014
DD	0.2820	0.137 +/- 0.0047
EE	0.4204	0.067 +/- 0.0028
FF	0.1075	0.303 +/- 0.008
GG	0.1550	0.360 +/- 0.0198
HH	0.0650	0.028 +/- 0.0019
II	0.3599	0.142 +/- 0.008
JJ	0.0328	0.035 +/- 0.0019
KK	0.0186	0.037 +/- 0.0019
LL	0.2201	0.147 +/- 0057
MM	0.0667	0.042 +/- 0.0024
NN	0.3992	0.256 +/- 0.008
OO	0.0926	0.126 +/- 0.0047

Table 4

Inleakage in Chemical Process Plant Control Rooms

(from Reference 9)

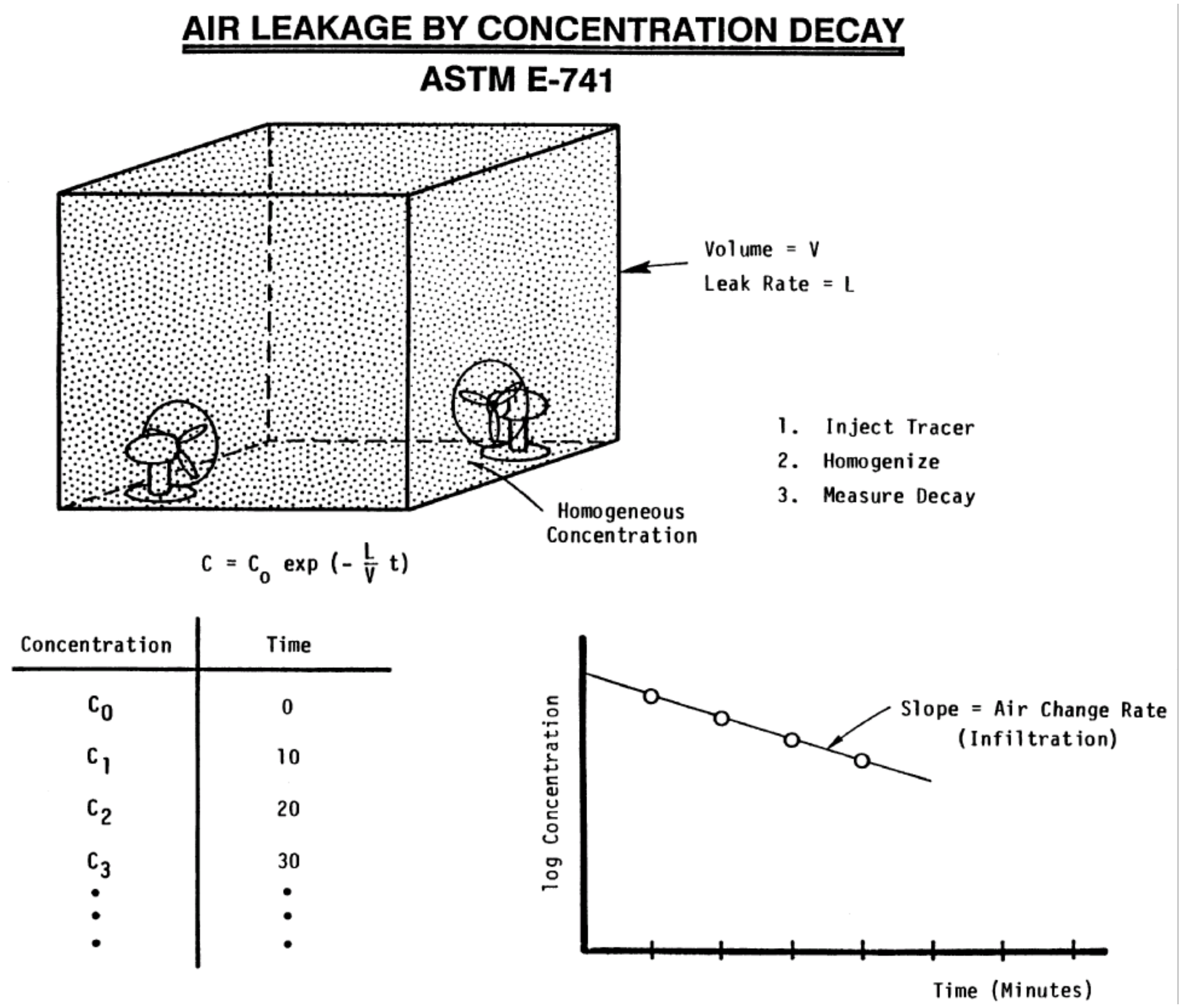
Plant	Inleakage (ACH)	Inleakage (m3/sec)
A	0.21	0.685
B1 (1984)*	1.95	0.840
B1 (1987)*	0.19	0.084
B2	0.20	0.138
C1	3.13	1.96
C2	0.05	0.050
C3	0.67	0.035

* An extensive sealing effort was undertaken in this control room after the 1984 testing and prior to retesting in 1987

Table 5

Sources of Inleakage into Control Rooms

Source	**Frequent**	**Infrequent**
Return duct seams (especially Pittsburgh seam)	X	
Return duct access doors and hatches	X	
Fan shaft seals on return legs of ductwork	X	
Air Handling Unit Housings	X	
Fan Vibration Isolation Boots		X
Isolation Dampers	X	
Return duct penetrations		X
Actuator shaft penetrations		X
Joints, penetrations, cracks in boundary (floor, walls, ceiling)		X
Personnel access doors		X
Non emergency duct(s) traversing control room		X



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

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

Figure 1. Tracer Concentration Decay Test

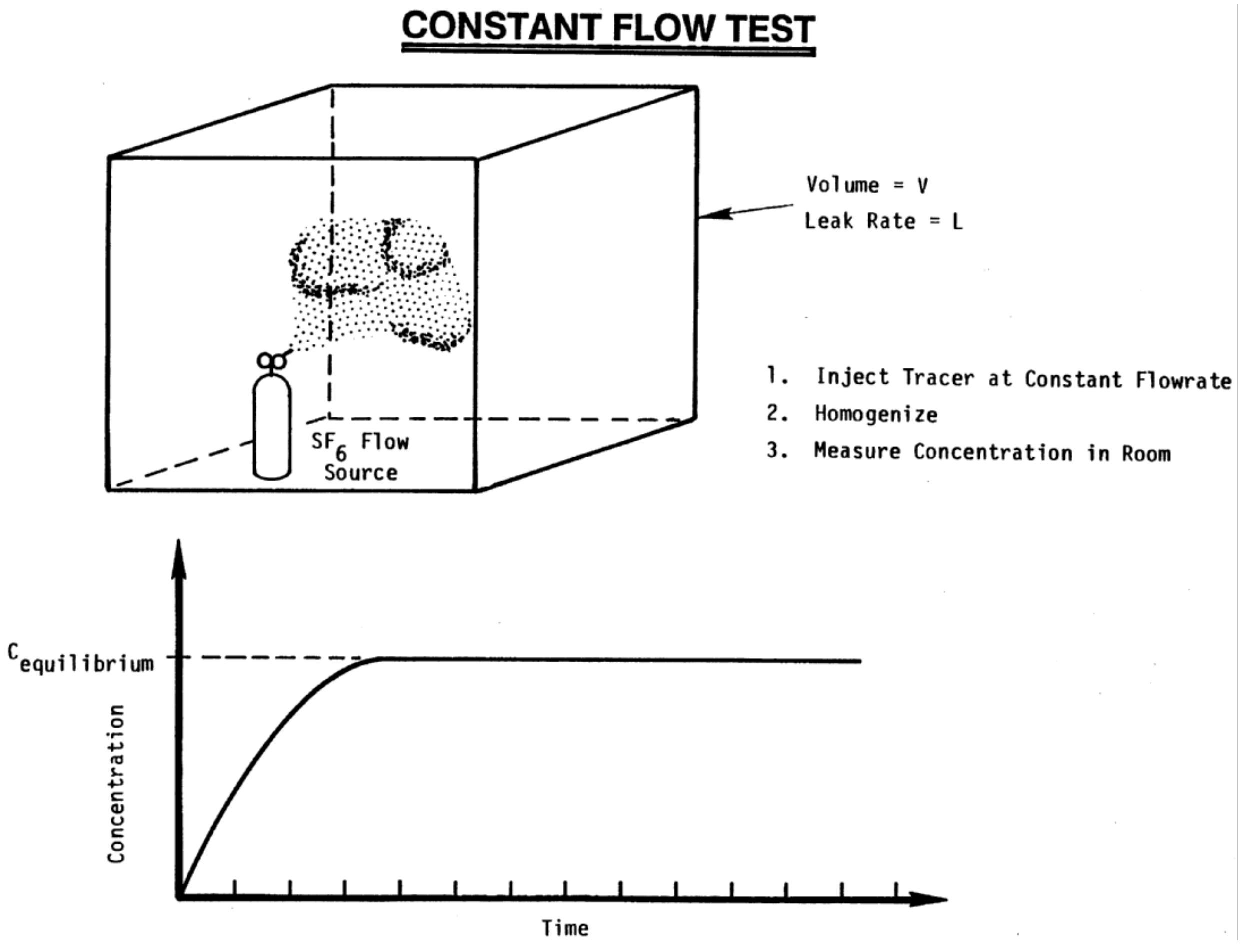


Figure 2. Concentration buildup/steady state test.