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# Air Inleakage Measurements in High Equilibrium Time Control Room Envelopes

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With the publication of Generic Letter 2003-01, every nuclear power plant in the U.S. has been required to document their unfiltered air inleakage into the Control Room Envelope during operation of the Control Room Emergency Ventilation System. In order to validate assumptions used in GDC 19 analyses of operator dose, most plants either have measured the unfiltered air inleakage or are planning to do so in the near future using a tracer gas test in conjunction with some variant of ASTM Standard E741 “Standard Test Method for Determining Air Change Rate in a Single Zone by Means of a Tracer Dilution” .

For plants that pressurize the Control Room Envelope during emergency operation, the so-called Concentration Buildup/Steady State technique is often used. However for those Control Room Envelopes with a very low makeup flow rate and 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.

In this paper we present an experimental technique that allows measurement of unfiltered inleakage into an operating nuclear power plant Control Room Envelope for low makeup flowrate (i.e. high equilibrium time) systems. This technique is based on the use of ASTM Standard E741 in conjunction with ASTM Standard E2029 “Standard Test Method for Volumetric and Mass Flow Rate Measurement in a Duct Using Tracer Gas Dilution”

Experimental data is provided for several plants. An uncertainty analysis of the measured data using ANSI/ASME Standard PTC 19.1 is provided for each inleakage value presented.

## 1.0 Introduction

With the publication of Generic Letter 2003-01 [1], every nuclear power plant has been required to measure unfiltered air inleakage into the Control Room Envelope (CRE) during operation of the Control Room Emergency Ventilation System (CREVS) in order to validate assumptions used in GDC 19 analyses of operator dose. Most plants have measured the unfiltered air inleakage or are planning to do so using a tracer gas test in conjunction with some variant of ASTM Standard E741 “Standard Test Method for Determining Air Change Rate in a Single Zone by Means of a Tracer Dilution”[2].

For plants that pressurize the Control Room Envelope during emergency operation, the so-called Concentration Buildup/Steady State technique is often used. However for those Control Room Envelopes with a very low makeup flow rate and a correspondingly low air exchange rate, the time to concentration equilibrium can be unreasonably long (as much as 100 hours!). This presents a severe experimental challenge to undertaking an air inleakage test.

Obviously, contractor and plant support personnel costs for a test that extends to times greater than a single shift can be significantly higher than for shorter tests. Coordination of a test that runs for significantly longer than a single control room operator shift represents a severe operational challenge. In addition most plants prefer to minimize the run time on their critical CREVS components due to NRC-mandated testing requirements after prescribed operating intervals have elapsed.

In this paper we present an experimental technique that allows measurement of unfiltered inleakage into an operating nuclear power plant Control Room Envelope for low makeup flowrate (i.e. high equilibrium time) systems. This technique is based on the use of ASTM Standard E741 in conjunction with ASTM Standard E2029 “Standard Test Method for Volumetric and Mass Flow Rate Measurement in a Duct Using Tracer Gas Dilution”[3].

## 2.0 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. At the present time the constant concentration method is primarily used by researchers in the building physics community and will not be discussed further in this paper.

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,

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

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 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. The units of A are air changes per hour ($h^{-1}$ or ACH). The value of A represents the volume-normalized 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 Technique

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 and assuming A is constant, a solution to equation (1) is;

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

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

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 room volume from which,

$$L = A \cdot V \qquad (4)$$

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. Thus, the experimental challenge is to assure that good mixing of the tracer gas is achieved.

## 2.2 Concentration Buildup/Steady State Technique

With the CREVS operating in a Pressurization Mode, air inleakage testing is often performed using the constant injection method, also known as the concentration buildup/steady state technique. This method measures the equilibrium tracer concentration within a ventilated area. This equilibrium concentration can be related to the airflow 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.

For the constant injection technique S(t) = constant. If A is also assumed to be constant, a solution to equation (1) is,

$$C(t) = (S/L) + (C_0 - S/L) \exp(-A \cdot t) \qquad (5)$$

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 (according to ASTM Standard E741 at least equal to approximately 3/A), the transient dies out and concentration equilibrium occurs. Equation (4) then becomes the simple constant injection equation,

$$C = S/L \qquad (6)$$

The reason that this technique is often preferred for the measurement of inleakage is that the result is ***independent*** of the volume of the CRE when the concentration value is at equilibrium. Often in the nuclear power plant context there is confusion as to the exact value for the volume of the CRE.

Inspection of equation (6) in light of equation (5) discloses that equilibrium is attained when the exponential term exp(-A*t) is negligible (ideally equal to zero) so that the term [1-exp(-A*t)] is approximately equal to one. ASTM Standard E741 states that this occurs at a time of 3/A. However, as can be seen from Table 1, this is not strictly correct.

In Table 1 we provide value of the term [1-exp(-A*t)] expressed as a percentage for various times. When the percentage equals 100%, equation (5) becomes equation (6). As can be seen, rather than for time 3/A but rather for times between 4/A and 5/A, equilibrium has been attained for all practical purposes. As an example, for a plant with a CRE volume of 150,000 cubic feet and a makeup flow of 600 CFM the value of A is 0.24 air changes per hour (ACH).

Referring to Table 1 we can see that between approximately 16.7 hours and 20.8 hours are required to achieve equilibrium. Hence tracer sampling to determine inleakage must wait for this period of time to elapse. In an inleakage measurement using the Concentration Buildup/Steady State Technique it is important to attain concentration equilibrium because if one uses concentration measurements to calculate inleakage *before* equilibrium is achieved, *the value of inleakage will always be* ***larger*** *than the true value attained at equilibrium.*

Waiting for such an extended period of time (as shown in Table 1) is not practical within the nuclear power plant CRE inleakage context. Any test that requires limiting access to the CRE for more than the duration of one shift (usually the back shift) is difficult if not impossible to implement. Accordingly a slightly different test technique based on ASTM E741 can be used. This test is described in section 2.4.

## 2.3 Tracer Gas Flow Rate Measurement

For many years it has been known that a method to measure duct flow rates exists other than Pitot tube or hot wire anemometer traverses. This other method entails the use of a tracer gas dilution method. This method is a *volumetric* as opposed to a point measurement. 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 point downstream of the injection point and the concentration of tracer gas 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 flow rate to the diluted concentration, $C_{av}$--in symbols:

$$L = S / C_{av} \qquad (7)$$

The tracer gas method relies on the use of a tracer gas to infer flow rate through a section of duct. An individual flow rate test is performed by injecting a tracer gas at a known rate into a section of duct upstream of a point and then measuring the equilibrium tracer gas concentration downstream of that point.

This equilibrium concentration in the duct is inversely proportional to the flow rate through the duct (as given by equation (7)). Thus, the measured concentration allows calculation of the flow rate since the injection flow rate is known. The basic test setup is shown in Figure 3.

One can rewrite equation (7) to explicitly reflect this measurement as equation (8),

$$L_{m/u} = S / C_{m/u} \qquad (8)$$

where, $L_{m/u}$ , is now the fresh air makeup flow rate.

During Makeup Flowrate/Concentration Decay testing, makeup airflow rates can be measured using the Tracer Gas Dilution Method described in ASTM Standard E2029. All makeup flowrates presented in this paper were measured in this way.

## 2.4 Makeup Flowrate/Concentration Decay Test

In a Makeup Flowrate/Concentration Decay Test, tracer gas is continuously injected into the makeup air stream of the CREVS at a constant rate while the makeup flowrate is measured. Tracer gas is then injected into the CRE for an additional period of time in order to achieve a concentration of 20 to 30 parts per billion after which injection is stopped and the tracer gas is allowed to disperse throughout the CRE.

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 CRE volume allows calculation of the Total Air Inflow rate in CFM. Note that this Concentration Decay Test is the first test type described in ASTM Standard E741.

Makeup flowrates 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 flowrate extant during the testing. Knowledge of the makeup flowrate in combination with a measured Total Air Inflow value allows calculation of the amount of air inleakage to the CRE that is not provided by makeup flow by differencing these two measured values.

## 2.5 Control Room Envelope Inleakage Measurement

In an air inleakage testing program using the Makeup Flowrate/Concentration Decay technique, the Total Air Inflow rate into the CRE is measured using equation (4). Tracer gas is injected into the supply side of the CRE ventilation system and, after waiting for concentration mixing to occur, a number of measurements of the resulting concentration within the CRE are obtained. Rewriting equation (4) yields the following:

$$L_{tot} = A*V \qquad (9)$$

Where $L_{tot}$ now represents the Total Air Inflow rate into the CRE. $L_{tot}$ is made up of two components, namely, the amount of makeup air, $L_{m/u}$ and the amount of air inleakage, $L_{inleak}$ .

Making use of these quantities, we can write an expression for the Total Air Inflow rate to the CRE as;

$$L_{tot} = L_{m/u} + L_{inleak} \tag{10}$$

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

$$L_{inleak} = L_{tot} - L_{m/u} \tag{11}$$

Since $L_{m/u}$ can be measured independently by using a tracer flow measurement technique, it is possible to calculate the Air Inleakage into the CRE using equation (11).

We should note that one can differentiate between filtered and unfiltered inleakage using the concepts provided in a prior technical paper [4].

## 2.6 Uncertainty Calculations

In this paper, the uncertainty of each CRE air inleakage measurement or duct flow rate measurement is calculated using the prescription provided in ANSI/ASME Standard PTC 19.1-1985 (Reaffirmed 1990) "Measurement Uncertainty" [5] and represent 95% confidence limits. This analysis is based upon equation (11) for the makeup flowrate/concentration decay tests, equation (8) for flow rates, and equation (4) for concentration decay test. Uncertainties for all derived and measured quantities are incorporated into the analysis.

Note that to use PTC 19.1 we assume that the data are distributed normally. Statistical tests can be used to verify this assumption but these tests are not performed on the data presented since only a small number data points are obtained for each inleakage value.

## 3.0 Plant Parameters

In the following we provide data obtained at four different nuclear power plants. For the purposes of this paper they will be referred to as Plants A, B, C, and D. All four plants incorporate at least one CREVS pressurization mode upon receipt of an emergency signal. Makeup flowrates, CRE volumes, and makeup flowrate air exchange rates are provided for each plant in Table 2.

The corresponding equilibrium time for each plant is provide in Table 3. Clearly the required times are longer than can be conveniently accommodated within a single operating shift at a typical plant since this period of time must elapse *before* inleakage measurements can commence.

### 3.1 Measurement using the Makeup Flowrate/Concentration Decay Technique

For all four of the plants tested, the basic test procedure used was as follows. Initially three distinct makeup flowrate measurements were performed using the concepts described in ASTM Standard E2029. This entailed using an SF6 injection concentration that did not result in a substantial increase in concentration within the CRE.

After this initial set of makeup flowrate measurements, SF6 at a higher concentration than that used in the makeup flowrate measurement was injected to raise the CRE concentration to between 20 ppb and 30 ppb. After waiting approximately one hour after injection of the higher concentration tracer gas mixture to allow for mixing of the tracer gas within the CRE, a concentration decay test as described in ASTM Standard E741 was performed. This portion of the test usually lasted two hours during which time a large number of spatially separated and representative samples were obtained at 30 minute intervals.

Upon completion of the decay test, a second series of three makeup flowrate measurements were performed. The six individual makeup flowrate measurements were averaged to obtain the mean makeup flowrate extant during the entire test.

Using the known volume of the CRE a Total Air Inflow was calculated from the concentration decay data using equation (9).

Using equation (11) the inleakage was then calculated. The calculated Inleakage data are summarized in Table 4. The third column in this table provides the inleakage value with its attendant 95% confidence value. The fourth column of the table provides only the value of inleakage since Regulatory Guide 1.197 Section 1.4 [6] states that Inleakage rates below 100 CFM do not require uncertainty value.

For all four of these plants the measured inleakage represented unfiltered inleakage.

### 3.2 Volume Effect on Measurement Uncertainty

As described previously, the exact volume of the CRE for a particular plant often is unknown. This lack of knowledge is a major reason for choosing to measure inleakage using the Buildup/Steady State Technique. However for those plants where this technique is impractical, it would be useful to understand the magnitude of the effect that imprecise knowledge of CRE volume has on the measured inleakage value. To do this we must first discuss the calculation of uncertainty in the context of inleakage measurements

For the test data provided in Table 4 the 95 % confidence limits were calculated using the concepts provided in ANSI/ASME PTC 19.1. Note that the uncertainty values in Table 4 all assume a 5 % uncertainty in the CRE volume.

The underlying reason to assess uncertainty using a confidence interval approach is that usually only a small number of measurements are performed in an operating nuclear power plant. Due to cost and operational considerations it is not generally feasible to undertake a large enough number of essentially identical tests in order 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.

We must note that uncertainty values that are reported as 1 standard deviation encompass only 68% of the variation in a data set with random uncertainties and does not provide any indication of the effect of systematic (bias) uncertainties on the overall uncertainty of a measurement.

A 95 % confidence limit simply means that if a measurement is repeated 100 times, the actual value will lie between the upper and lower confidence limits 95 of those times. For example if an inleakage value of 200 CFM is measured with a 95 % confidence limit of 50, repeating the measurement 100 times would result in 95 of the values lying between 150 CFM and 250 CFM.

Mathematically the confidence interval is described by the following equation [7]:

$$U_{95} = \pm\left[\sum_i B_i^2 + \sum\left(t_i \bullet S_i\right)^2\right]^{1/2} \tag{12}$$

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 flowrate measurement uncertainty.

Sources of random uncertainty include makeup flowrate uncertainty, Total Air Inflow uncertainty, and CRE volume uncertainty.

In Table 5 we present the same data as provided in Table 4. However in Table 5, we provide inleakage uncertainty values assuming 0%, 5%, 10%, and 25% uncertainties in the knowledge of CRE volume. All other uncertainties as enumerated above were held constant. It is unlikely that CRE volumes are unknown by more than +/- 10% but the 25 % value is provided for information.

An alternative approach is to use the geometric volume of the CRE. Use of the physical or geometric volume implies that the volume uncertainty is zero. Hence the uncertainty values calculated for the 0% Uncertainty column would apply. A potential problem with this approach is that for certain CRE configurations the calculated inleakage using the geometric volume may lie above 100 CFM. It may be that the net volume of the CRE may be sufficiently less than the geometric volume so that the calculated inleakage value would lie below rather than above 100 CFM. By net volume we mean the volume of the CRE that actually exchanges air with other portions of the CRE.

Since Regulatory Guide 1.197 Section 1.4 states that inleakage rates below 100 CFM do not require uncertainty value, it is often prudent to consider whether a reduced CRE volume is appropriate. This may be important since adding the uncertainty value to a measured inleakage value can sometimes substantially increase the inleakage value used in the GDC 19 CRE habitability calculation.

One must be careful to exclude only those volumes that definitely do not exchange air with the CRE. The volume of completely sealed and non-ventilated enclosures, the volume of ductwork traversing the CRE that is not part of the CREVS, and the volume of solid structural components can be safely eliminated from the calculation of the net CRE volume. As a general rule, if there is doubt as to whether a particular object within the CRE exchanges air, it should not be removed from the calculation of the net volume of the CRE.

## 4.0 Conclusions

For nuclear power plant Control Room Envelopes that pressurize in response to a radiological emergency, it is prudent to measure inleakage using the Buildup/Steady State technique, since at equilibrium the volume of the CRE does not affect the calculation of inleakage.

For those plants that exhibit a low air exchange rate (makeup flow/CRE volume) with a correspondingly long concentration equilibrium time, it is possible to use a Makeup Flowrate/Concentration Decay Technique.

For the four data sets presented in this paper, it would have required between 10.5 and 174 hours to achieve concentration equilibrium at the 4/A value of time (98.2% of the equilibrium tracer gas concentration) prior to undertaking an inleakage test using the Concentration Buildup/Steady State Technique. In contrast all four data sets were easily obtained during a single evening shift at the four plants tested.

## 5.0 References

[1] Generic Letter 2003-01 “Control Room Habitability”, US Nuclear Regulatory Commission, Washington DC, June 2003

[2] ASTM Standard E741-00, “Standard Test Method for Determining Air Change Rate in a Single Zone by means of a Tracer Dilution”, ASTM, Philadelphia. PA, 2000.

[3] ASTM Standard E2029-99, “Standard Test Method for Volumetric and Mass Flow Rate Measurement using Tracer Gas Dilution”, ASTM, Philadelphia. PA, 1999.

[4] Lagus, P.L., “Component Leakage Testing using Tracer Gas Techniques” in the Proceedings of the 27th NRC/DOE Air Cleaning and Treatment Conference, Nashville, TN, 2002.

[5] ANSI/ASME Standard PTC 19.1 1985 (Reaffirmed 1990), Part 1, “Measurement Uncertainty: Instruments and Apparatus”, American Society of Mechanical Engineers, New York, NY, 1990.

[6] Regulatory Guide 1.197, “Demonstrating Control Room Envelope Integrity at Nuclear Power Reactors”, US Nuclear Regulatory Commission, Washington, DC, May 2003

# TABLE 1

Times to Equilibrium
(CRE Volume of 150,000 Cubic Feet, Makeup Flowrate of 600 CFM)

| 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

Plant Data

| Site | CRE Volume ($Ft^3$) | Makeup Flowrate (SCFM)* | Air Exchange Rate (ACH) |
|---|---|---|---|
| Plant A | 79,800 | 248 +/- 9 | 0.186 |
| Plant B | 254,000 | 96 +/- 6 | 0.023 |
| Plant C | 360,000 | 1847 +/- 82 | 0.308 |
| Plant D | 141,400 | 896 +/- 39 | 0.380 |

* For plants with redundant trains, the higher rate makeup rate is used in these calculations.

# TABLE 3

Equilibrium Times (in Hours)

| Site | 3/A | 4/A | 5/A |
|---|---|---|---|
| Plant A | 16.1 | 21.5 | 26.9 |
| Plant B | 130 | 174 | 217 |
| Plant C | 9.7 | 13.0 | 16.2 |
| Plant D | 7.9 | 10.5 | 13.2 |

# TABLE 4

Measured Inleakage Values

| Site | Makeup Flowrate (SCFM) | Inleakage (ACFM) | Inleakage (ACFM)** |
|---|---|---|---|
| Plant A | 248 +/- 9* | 53 +/- 18* | 53 |
| Plant B | 96 +/- 6* | 36 +/- 10* | 36 |
| Plant C | 1847 +/- 82* | 66 +/- 135* | 66 [a] |
| Plant D | 896 +/- 39* | 12 +/- 63* | 12 [b] |

* 95 % Confidence Value Uncertainty
** Per Reg Guide 1.197 Section 1.4 Inleakage rates below 100 CFM do not require uncertainty value
a Statistically Zero (?) Value
b Statistically Zero Value

# TABLE 5

Effect of CRE Volume Uncertainty on Inleakage Uncertainty (in CFM)

| Site | Inleakage (ACFM) | 0% Volume Uncertainty | 5% Volume Uncertainty | 10% Volume Uncertainty | 25% Volume Uncertainty |
|---|---|---|---|---|---|
| Plant A | 53 | 10 | 18 | 32 | 76 |
| Plant B | 36 | 8 | 10 | 15 | 34 |
| Plant C | 66 | 95 | 135 | 214 | 488 |
| Plant D | 12 | 44 | 63 | 101 | 231 |

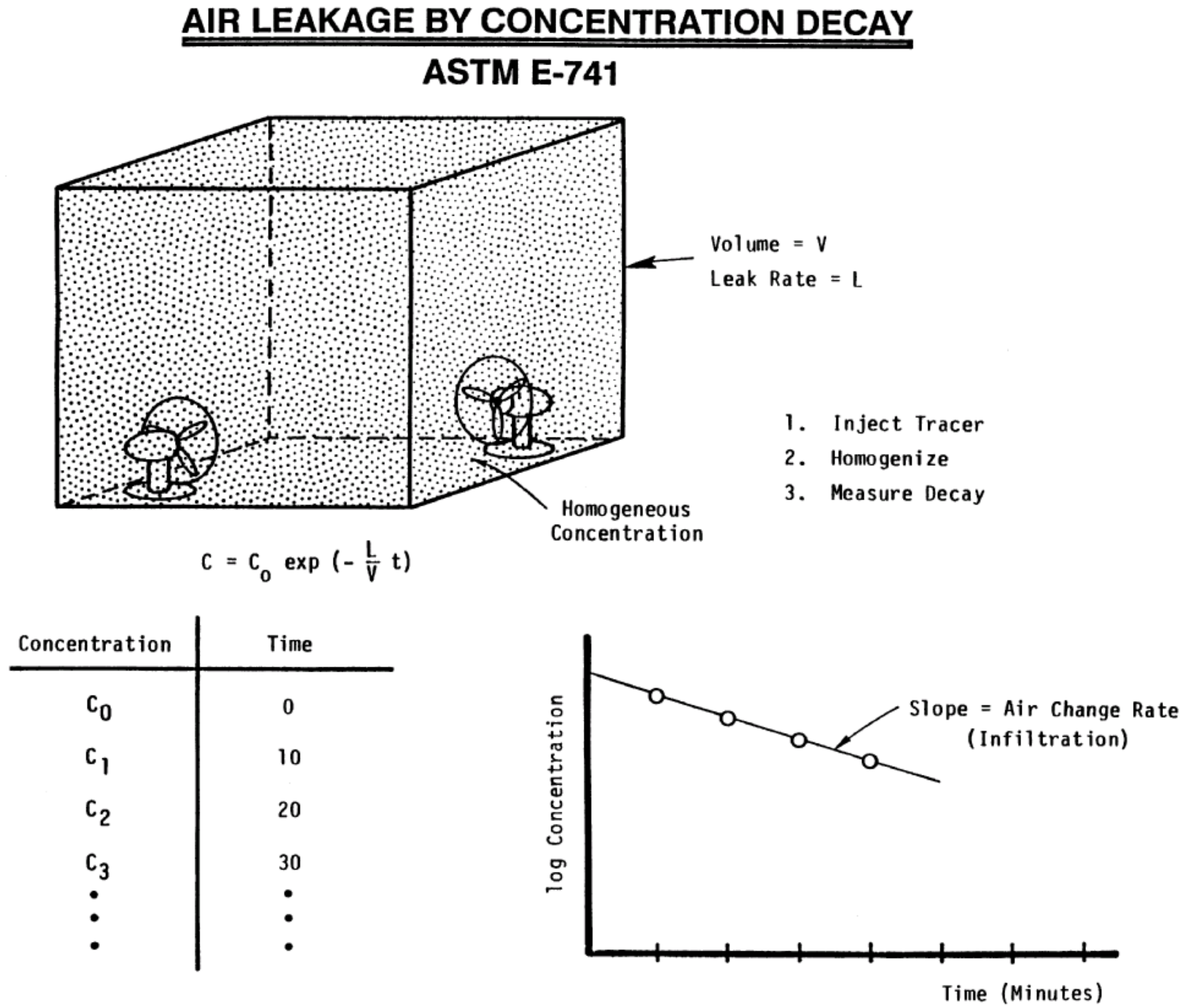


Figure 1. Concentration Decay Test

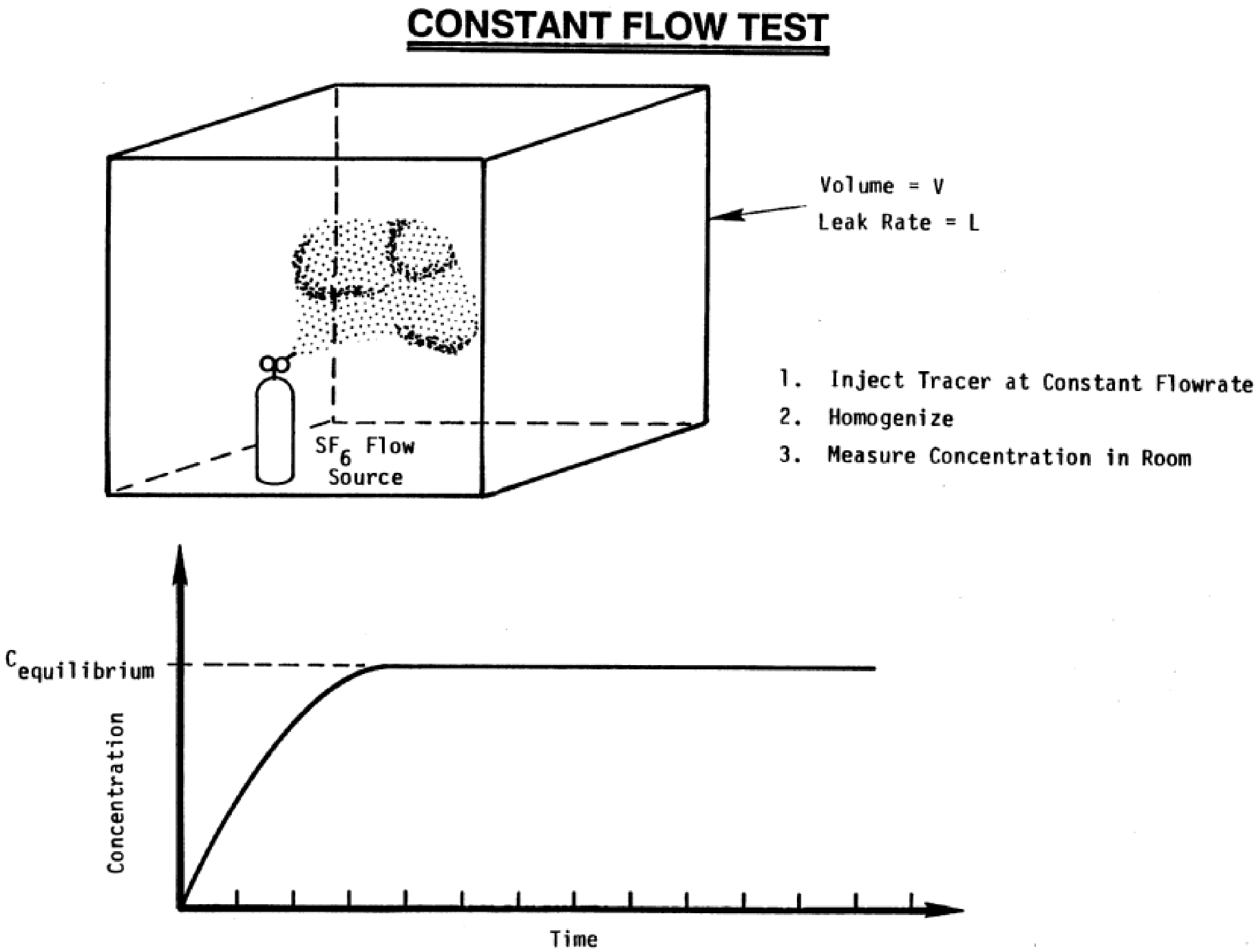


Figure 2. Concentration buildup in test volume as function of time.

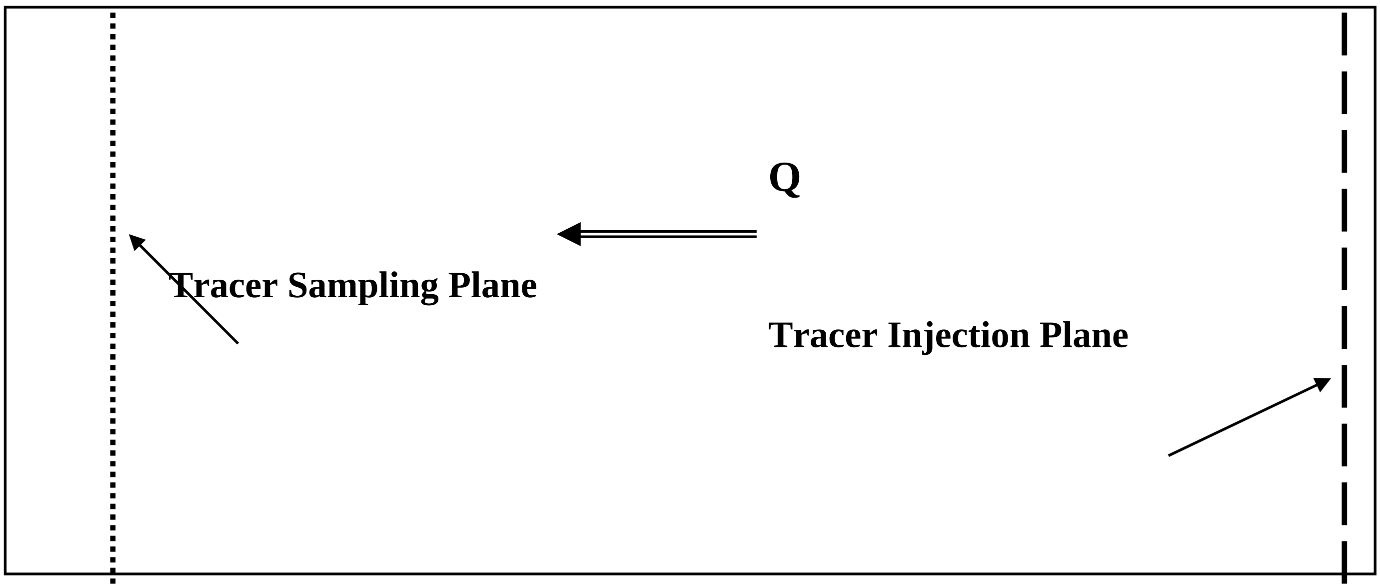


Figure 3. Schematic representation of tracer gas flow rate test.