24th DOE/NRC NUCLEAR AIR CLEANING AND TREATMENT CONFERENCE

CONTROL ROOM ENVELOPE UNFILTERED AIR INLEAKAGE TEST PROTOCOLS

Peter L. Lagus, Ph.D., CIH
Lagus Applied Technology
San Diego, CA 92121

Richard A. Grot, Ph.D.
Lagus Applied Technology
Olney, MD 20832

ABSTRACT

In 1983, the Advisory Committee on Reactor Safeguards (ACRS) recommended that the US NRC develop a control room HVAC performance testing protocol. To date no such protocol has been forthcoming. Beginning in mid-1994, an effort was funded by NRC under a Small Business Innovation Research (SBIR) grant to develop several simplified test protocols based on the principles of tracer gas testing in order to *measure* the total unfiltered inleakage entering a CRE during emergency mode operation of the control room ventilation system. These would allow accurate assessment of unfiltered air inleakage as required in SRP 6.4.

The continuing lack of a standard protocol is unfortunate since one of the significant parameters required to calculate operator dose is the amount of unfiltered air inleakage into the control room. Often it is *assumed* that, if the Control Room Envelope (CRE) is maintained at +1/8 in. w.g. differential pressure relative to the surroundings, no significant unfiltered inleakage can occur it is further assumed that inleakage due to door openings is the only source of unfiltered air.

The specific technical objectives of the effort were:

1) to define three simple tracer gas tests that would allow accurate measurement of CRE unfiltered air inleakage,

2) to define those additional engineering parameters knowledge of which would be required for each basic type of emergency ventilation system to allow measurement of unfiltered inleakage,

3) to provide a thorough error analysis of the inleakage measurement technique(s) so that defensible bounds could be placed on any resulting data, and

4) to generate test protocols based on the above three objectives that would allow measurement of unfiltered air inleakage by responsible plant personnel.

This paper summarizes the test protocols that were developed and discusses the accuracy to be expected from each of them.

1.0 INTRODUCTION

In 1983, the Advisory Committee On Reactor Safeguards (ACRS) provided a series of recommendations to the NRC regarding control room habitability (Hayes, et al., 1984). One of the ACRS concerns was that NRC did not have a protocol for testing control room heating ventilating and air conditioning (HVAC) systems. It was recommended that the NRC develop such a protocol. Writing in the 18th DOE Nuclear Airborne Waste Management & Air Cleaning Conference, members of the ACRS observed "The NRC staff needs to expedite it's efforts to develop a protocol for testing control room HVAC and air cleaning systems. Such tests should be conducted under realistic operating conditions.....all parts of the systems including dampers, ducts, etc. should be tested simultaneously as an integral unit.....particular attention should be given to assure that sections of such systems that are under negative pressure will not bring in contaminants which later can be transferred to the control room." (Moeller and Kotra, 1984).

As of early 1995, no control room HVAC performance testing protocol has been put forward by NRC. This lack of a standard test protocol is particularly unfortunate in light of the methodology used to calculate control room staff doses (Murphy and Campe, 1974, Stage, 1995). One of the significant parameters contained within either formalism is the amount of unfiltered air inleakage into the control room.

Present practice appears to assess inleakage based on models of air flow through cracks combined with assumed pressure differences. Often it is *assumed* that if the CRE is maintained at +1/8 in. w.g. differential pressure relative to the surroundings, no significant unfiltered inleakage can occur and that inleakage due to door openings is the only source of unfiltered air. Theoretically this can be true *only* if no portion of the return leg (or legs) of the CRE emergency ventilation system lies outside the CRE.

Negative differential pressure portions of return ducting, fan shaft seals, expansion boots, control dampers, ventilation fan or filter access panels, actuator shaft seals, and miscellaneous unsealed penetrations that lie outside the CRE can contribute substantial unfiltered air inleakage. Other sources of unfiltered air inleakage include improperly seated low leakage intake dampers and leakage from HVAC supply ductwork that traverses the CRE, but provides airflow to non-CRE portions of the building.

Sometimes, unfiltered air inleakage is extrapolated from simple fan pressurization test data. Such an extrapolation is usually unwarranted since the pressure conditions that exist in a ventilation system/control room envelope under emergency operating conditions may not be the same as those generated by a fan pressurization test. ASTM Standard E779-87 (ASTM, 1992) which covers fan pressurization testing provides an explicit warning that extrapolation of fan pressurization data to actual operating conditions *is not feasible*.

It is often claimed that unfiltered air inleakage can be discerned by visual inspection coupled with a ventilation system walkdown. Sometimes this walkdown is augmented by use of smoke tracing to identify inleakage pathways. Since visual inspection is not quantitative, it can only discover obvious (open) leakage pathways and cannot deduce the magnitude of

potential inleakage due to any pathway so discovered. For inleakage sites that are hidden from view, visual inspection cannot discern their existence much less quantitatively assess the magnitude of any air inleakage into a CRE.

Smoke testing was originally developed for use in visualizing airflows in mines and has proven to be useful in following airflow patterns within a limited volume. However, it provides no *quantitative* estimate of actual unfiltered inleakage. In addition, care must be exercised in the interpretation of smoke flow patterns since the results often respond to localized airflows occurring at specific points within the CRE. Frequently, false indications of flow are caused by temperature gradients or transient atmospheric conditions that have nothing to do with actual inleakage.

In light of the above enumerated deficiencies of existing CRE inleakage testing techniques, a protocol based on the principles of tracer gas ventilation testing was felt to be appropriate. Tracer gas ventilation tests directly respond to the volumetric ventilation performance in the structure under test and hence do not possess the intrinsic drawbacks of the other methods.

The specific technical objectives of this effort were:

1. to define three simple tracer gas tests that would allow accurate measurement of control room emergency ventilation system operating characteristics, specifically unfiltered air inleakage, on a reconnaissance basis,
2. to categorize the various types of emergency ventilation systems and, having done so, to define those additional engineering parameters that may be required in addition to tracer gas data to allow interpretation of tracer gas data in terms of unfiltered inleakage,
3. to provide a thorough error analysis of the inleakage measurement technique(s) so that defensible bounds may be placed on any resulting data, and
4. to generate test protocols based on the above three objectives that would allow the performance by responsible plant personnel of a simple tracer test to measure unfiltered air inleakage.

Note that the test protocol developed in this effort would not, in general, disclose the actual location(s) of unfiltered inleakage, but only the total amount. For a reconnaissance measurement, this quantity is sufficient to decide if the unfiltered inleakage presents a problem in terms of compliance with GDC 19. To provide quantitative information as to leak location and magnitude requires more sophisticated testing than is being discussed in this paper.

2.0 TECHNICAL BACKGROUND

Tracer gases have been used to measure air infiltration and ventilation characteristics of buildings for over 30 years. Tracer gas techniques have been successfully used in other areas of ventilation engineering and industrial hygiene to provide accurate characterization of HVAC performance under actual operating conditions (Lagus and Persily, 1985, Grot and Lagus, 1991).

Within the nuclear power community, tracer gas techniques have been used since the early 1980's to measure, for instance, airflow patterns to investigate health and safety monitor locations (Hickey, et al., 1991) as well as to understand potential gaseous radioactive contaminant migration within selected buildings (Vavasseur, 1985, Lagus et al., 1988). Recently the results of a series of tracer gas measurements designed to measure total unfiltered inleakage into a nuclear power plant control room have been published (Lagus et al., 1992).

2.1 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 dilution method, the constant injection method, and the constant concentration method. All are based on applying the conservation of mass equation to a tracer gas concentration established in a test volume. The tracer dilution 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 within the volume as a function of time. The constant injection method is an indirect method, i.e., it measures the equilibrium tracer concentration within a ventilated area. This concentration can be related to the air flow rate if the tracer release rate is known. The constant concentration method is primarily a research method at this time and will not be discussed further. All three of these techniques are incorporated in the most recent revision of ASTM Standard E741-93 "Standard Test Method for Determining Air Change Rate in a Single Zone by Means of a Tracer Gas Dilution" (ASTM, 1993).

The mass balance equation and its various solutions that lead to the tests described above, have been provided in previous papers (Lagus and Persily, 1985, Grot and Lagus, 1991) and hence will not be reproduced here. These methods allow determination of either A or q. 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), V is the test volume, and q(t) is the volumetric airflow rate into (or out of) the test volume. In the simplest case, the value of A represents the flowrate of "dilution air" entering the volume during the test interval. Note that this "dilution air" can be actual outside fresh air or, more generally, it can be air whose origin is not within the test volume.

2.2 TRACER GAS MEASUREMENT TECHNIQUES

Instrumental techniques used to measure tracer gas concentrations are listed in Table 2.1, along with some of the gases appropriate to each measuring instrument. All of the gases listed have been used for airflow measurements either within buildings or within individual rooms. Several characteristics of nuclear power plant CREs influence the manner in which tracer techniques are applied. First, because of the large volumes, the quantity (and therefore cost) of tracer gas required for a test becomes important. The expense depends on the cost per unit volume of tracer gas, the CRE volume, and the magnitude of the lowest tracer concentration measurable. Table 2.2 shows the range of maximum volumes that can be measured for one dollars worth of tracer gas (1994 prices). These volumes range from about 9000 Ft^3 for helium to about 5.6×10^{10} Ft^3 for SF6.

Carbon dioxide exhibits an atmospheric background of approximately 350 ppm and is also generated by both combustion sources and human metabolism. Accordingly, it is difficult to assure that a non-variable background of CO2 is maintained during a particular testing interval. In fact, detailed review and studies undertaken by the National Institute for Standards and Technology (NIST) have concluded that except for a limited set of circumstances, the use of CO2 as a ventilation tracer gas is inappropriate (Persily, 1993).

Nitrous oxide has been used as a tracer gas primarily by European researchers. However, N2O exhibits a Threshold Limit Value (TLV) of 50 ppm and hence may not be an appropriate choice for control room testing where test duration may approach eight hours. In the United States, health concerns related to the TLV of N2O have resulted in little use of N2O as a tracer.

The fact that SF6, some halocarbons and some perfluorocarbons can be measured to levels of 10 parts per trillion and below yields maximum measurable volumes in the range of 5×10^8 to 5.6×10^{10} Ft^3 per dollars worth of tracer gas. From Table 2.2 it is apparent that these gases (analyzed at the five to ten part per trillion level or even the part per billion level) are most appropriate for the large volumes encountered in Control Room Envelopes.

2.3 TRACER GAS MIXING

Because of the relatively large volume of the CRE, mixing of tracer gas is an important issue. Mixing by molecular diffusion is a slow process; however, even in naturally ventilated enclosures, there are significant convective mixing mechanisms. In mechanically ventilated environments, the air distribution system has been shown to be effective at mixing of the tracer gas (Grot and Persily, 1986). Experimentally, portable fans have been used to augment mixing of tracer at the expense of altering internal air movement patterns. The attainment of a uniform concentration can also be assisted by injecting tracer gas at several locations.

The issue of mixing of tracer gas in the CRE volume is of critical importance to the measurement and interpretation of concentration decay measurements in the determination of unfiltered inleakage. In order for the solutions to the mass conservation equation to be valid for the *entire* CRE volume it is required that the tracer be well mixed, i.e., the measured concentration anywhere in the volume is only a function of time. In practice, concentration homogeneity is taken to be +/- 10 % or better throughout the test volume (as specified in ASTM Standard E741).

A number of selected references in the published literature provide data supporting the feasibility of attaining "good mixing" of tracer within a test volume. In general, these references provide experimental tracer concentration data which show that mixing occurs fairly rapidly (within thirty minutes to, at most, one hour) in ventilated rooms or entire buildings ranging in volumes from 76 m^3 up to over of 10^5 m^3 (Alevantis and Hayward, 1990, Evans and Shaw, 1988, Shaw et al., 1993, Reardon et al., 1994).

Previous measurements by the authors in two control rooms (one a single story CRE with a volume of approximately 1700 m^3 and the other a two story CRE with a volume of approximately 4000 m^3) that were mechanically ventilated, demonstrated that it was possible to attain concentration variations of less than +/- 2% in the single story CRE and less than +/- 5% in the two story CRE, by including of a number of auxiliary mixing fans at various points with the volumes.

ASTM Standard E741 suggests that inleakage can be measured using a tracer gas technique with an error of 10% or less of the measured value. The experimental conditions considered in the examples of this study suggest that errors of half (i.e. approximately 5%) of this value are attainable.

Note that most of the instrumental techniques utilize electron capture detector gas chromatography for measurements in large volumes primarily due to tracer gas cost considerations. However, measurements have been performed in large buildings using other techniques such as infrared absorption (Potter et al., 1983, Zeurcher and Feustel, 1983) and flame ionization gas chromatography (Prior et al., 1983).

3.0 CONTROL ROOM ENVELOPE TEST METHODS

Four basic types of CRE emergency ventilation systems were considered:

1. Isolation of normal ventilation with filtered pressurization,
2. Isolation of normal ventilation with filtered recirculation,
3. Isolation of normal ventilation with filtered pressurization and recirculation,
4. Bottled Air for Pressurization.

All four basic ventilation types are amenable to a tracer gas decay test to determine unfiltered inleakage. Type 2 above can be measured by a simple tracer decay test, while types 1, 3, and 4 require both a tracer decay test and an independent measure of the pressurization flowrate.

3.1 TRACER DECAY TEST

The tracer decay test method requires only the measurement of relative tracer gas concentrations, as opposed to absolute concentrations, and the analysis required to determine A is straightforward. Equation (1) serves as a starting point for an actual test .

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

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 (7). The slope of this regression yields the air exchange rate, A. Knowledge of the volume, V, allows calculation of the leakage flowrate q since

$q = A*V$.

In the case of a CRE with makeup flow, the value of q (or A) determined is the total air inleakage rate. This will consist of the unfiltered inleakage and the actual makeup flow rate. For this case an independent determination of the makeup (or pressurization) flowrate, q_{makeup}, is required. The unfiltered inleakage is then determined as follows;

$$q_{unfiltered} = q - q_{makeup} \qquad (2)$$

where q is the rate determined from the tracer concentration decay measurement (and is equal to A*V) and now represents the total "fresh air" inleakage rate into the CRE. Equation (2) can be written

$$q_{unfiltered} = A*V - q_{makeup} \qquad (3)$$

In the case of a CRE with recirculation only (no makeup) then q (or A) measures the unfiltered inleakage *directly* and q_{makeup} would be identically equal to zero.

Standard statistical arguments applied to equation (3) lead to the following estimate of the uncertainty in the determination of $q_{unfiltered}$:

$$S_{qu} = SQRT\{ (S_A)^2 + (S_V)^2 + (S_{qm})^2 \} \qquad (4)$$

where S_{qu} = Probable error in the value of $q_{unfiltered}$
S_A = Probable error in the value of A
S_V = Probable error in the value of V
S_{qm} = Probable error in the value of q_{makeup}

In Figures 1 to 5 the probable error in a given value of unfiltered inleakage for several assumed error values in measured concentration, CRE volume and inleakage rate. The assumed measurement errors attendant to each case are described below:

- CASE I Error in V = 2%, Error in q_{makeup} = 3%, Error in A = 2%
- CASE II Error in V = 3%, Error in q_{makeup} = 5%, Error in A = 5%
- CASE III Error in V = 3%, No Makeup flow, Error in A =5%
- CASE IV Error in V = 5%, Error in q_{makeup} = 10%, Error in A = 10%
- CASE V Error in V = 5%, No Makeup flow, Error in A =10%

As can be readily seen, the error in the measured value of $q_{unfiltered}$ is never very large. The error in the measured value of unfiltered inleakage is smaller for those cases having recirculation only (no makeup air). For relatively modest measurement errors in the variables needed to obtain unfiltered inleakage, the error in the resulting unfiltered inleakage

remains moderate. Note that the measurement errors in Cases I, II, and III above are considered more representative of actual practice than those in Cases IV and V.

It is possible to use equation (1) to estimate the length of time required for a given measurement error. Taking differentials of C and A and rearranging, one arrives at

$$\text{TEST TIME} = \{2*(dC/C)\}/\{(dA/A)*A\} \qquad (5)$$

where (dC/C) = Concentration measurement error
(dA/A) = Total air exchange rate measurement error

Note that the test times calculated from equation (5) use the *end* points of the measured concentration decay, i.e. the calculation assumes that only two points are used to determine the slope of the line. By performing a regression analysis on a number of concentration data points as described above, it is possible to reduce the probable error in the measured value of A or the time required to achieve a given value of probable error.

To illustrate this, a number of regression analyses were undertaken on simulated concentration decay data to calculate the probable error in the "measured" value of A as a function of elapsed time. Two series of calculations were performed for several inleakage rates (corresponding to makeup rates from 100 to 800 CFM) assuming one data point every thirty minutes and also one every fifteen minutes. An additional series of calculations was undertaken in which the inleakage rate was fixed and the number of data points sampled at each measurement time was systematically increased.

Figures 6 and 7 show probable error for various inleakage rates as a function of total test time. For a sampling interval of thirty minutes, for all cases considered, the probable error does not drop below 15% in less than six hours. Decreasing the sampling time to fifteen minutes decreases the probable error to less than fifteen percent in a four hour test. Note also that as the inleakage rate *increases*, the probable error for a given test time *decreases*. For these simulations the measurement error was assumed to be +/- 2%.

Figure 8 demonstrates the effect of increasing the number of concentration data points taken at each sampling interval. This plot illustrates calculations for A = 0.125 ACH. For higher air leakage rates, the corresponding test times to attain a given probable error will decrease. Based on this calculation it appears that sampling at eight points every half hour will ensure that the probable error will lie below 5% within four hours assuming that the uncertainty in concentration is +/- 2%.

Figure 9 provides a similar calculation assuming the concentration measurement uncertainty is +/- 5%. In this case, by taking eight concentration data points per measurement interval, the probable error in the inleakage rate will be less than 10% for test times of four hours or more.

To assure that good mixing has been achieved, a careful experimenter should obtain at least four spatially separated samples at each sampling time. Based on the above examples, a four hour test will generate an inleakage value that is precise to within +/- 10% if the individual concentration data points differ by less than +/- 5%. Higher precision is possible if the scatter in the concentration data points at each time interval is less (i.e. mixing is better).

During the actual testing, ingress and egress to the CRE should be kept to an absolute minimum. Any necessary ingress and egress should be through a single door and accomplished as rapidly as possible. No more than two door openings should be allowed during each hour of testing. At no time during a test should *two* doors to the CRE be opened simultaneously. **If two doors to the CRE are opened simultaneously, any test results should be considered invalid.**

All internal ventilation fans (such as bathroom and kitchen ventilators) in the CRE should be turned off unless they remain in operation during an emergency. These fans should be disabled in such a way as to ensure that the fans will not be accidentally energized during a test.

To assist in attainment of a well mixed volume within the CRE, one auxiliary mixing fan should be provided for each 1,000 to 2000 ft^2 of CRE floor area. Fans should be arranged throughout the CRE area to enhance air movement within the CRE. For CREs having drop ceilings, experience has shown that removal of a small fraction (5% to 10%) of the ceiling panels coupled with the placement of several of the required mixing fans above the drop ceiling will enhance air flow across the drop ceiling boundary and hence, overall air mixing within the CRE. Air samples from above the drop ceiling should be analyzed to demonstrate that good mixing has been achieved.

3.1.1 TRACER DECAY TEST PROCEDURE

Tracer gas is injected into a CRE emergency ventilation supply duct at a rate calculated to achieve a desired concentration. Experience has shown that for mechanically ventilated structures, injection of a diluted mixture of tracer gas over approximately thirty minutes enhances the mixing of gas with the test volume.

Air samples from at least four, and as many as eight, spatially diverse locations within the CRE, should be obtained at thirty minute intervals. For most conditions likely to be encountered in testing unfiltered inleakage a maximum test duration of four hours should be used. Note that it is possible to terminate a test in less than four hours if the actual regression data indicate that a 95% probable error of less than 10% (5%) has been achieved in less time.

If the CRE incorporates makeup flow in its emergency operating mode, then this makeup flowrate should be measured using a pitot tube or hot wire traverse or a tracer flow technique both *before* and *after* the tracer decay test, and the results averaged.

3.1.2 CALCULATIONS

If the CRE does not provide makeup flow in the emergency ventilation mode, the value of A calculated by regression of the tracer concentration decay data is also the *unfiltered inleakage*.

If the CRE does provide makeup flow in the emergency mode, then the values of makeup flow measured Pre and Post test are averaged:

$$q_{makeup} = (\text{Pretest Makeup Flow} + \text{Post Test Makeup Flow})/2 \qquad (6)$$

The unfiltered inleakage is then given by equation (3) rewritten here as equation (7):

$$q_{unfiltered} = A*V - q_{makeup} \qquad (7)$$

Note that regression analysis should be performed after the first three sampling intervals and should be continued for each subsequent sample interval. When then 95% probable error calculated in the regression drops below 10% (or 5%), air sampling and analysis may be discontinued. As noted above, the maximum test interval contemplated in the tracer decay test is approximately four hours.

3.2 CONSTANT FLOWRATE TEST PROCEDURE

The constant flowrate test is an alternate technique that avoids the requirement for accurate knowledge of the CRE volume. Uncertainty in the accurate knowledge of CRE volume can contribute to the uncertainty in the final measured result. Also, for CRE's that exhibit high makeup air flowrates (values of A greater than approximately 1.5, or makeup flows of 2500 CFM for a 100,000 cubic foot CRE), tracer concentration decay may occur very quickly. Also, the tracer gas analyzer may not possess a sufficiently broad measurement range to encompass data taken over a four hour interval.

Accordingly a tracer test that uses a constant flowrate injection of tracer gas into the CRE while measuring the resulting concentrations at selected locations can be used. For the following derivation the return air system is included in the CRE volume. If it is assumed that the volume is well mixed, one can apply conservation of mass to the elements of a CRE shown in Figure 10, and arrive at equation (8):

$$Q_{in} = Q_{sup} ((C_{sup}/C_r) - 1) \qquad (8)$$

where Q_{in} = Inleakage (anywhere into CRE)
Q_{sup} = Total Supply Flowrate
C_{sup} = Equilibrium Concentration in Supply duct
C_r = Equilibrium Concentration at end of return duct

In deriving equation (8) it is assumed that tracer is injected at a constant flowrate into the supply duct.

Note that this expression does not require knowledge of the control room volume. Standard statistical arguments applied to equation (8) lead to the following estimate of the uncertainty in Q_{in} :

$$S_{inleak} = SQRT\{ (S_{qsup})^2 + (S_{csup})^2 + (S_r)^2 \} \qquad (9)$$

where S_{inleak} = Probable error in the value of Q_{in}
S_{qsup} = Probable error in the value of Q_{sup}
S_{csup} = Probable error in the value of C_{sup}
S_r = Probable error in the value of C_r

Note that there are the same number of terms in equation (9) as in equation (4), but two of them are related to the gas analyzer measurement error and one to the error in flowrate measurement. These errors are intrinsically more amenable to statistical treatment than is the control room envelope volume.

Figures 11 and 12 provide a graphical illustration of the uncertainty in the measured inleakage value using this technique. Note that what is plotted is the minimum measurable inleakage as a function of total supply flowrate (Makeup flowrate plus return flowrate). Any value of inleakage greater than the minimum shown can be determined reliably by this method. The fact that there is a minimum value of inleakage measurable by this technique arises from the ability of the measurement device to discriminate between two concentrations that are close in value. This technique is complementary to that provided in Section 3.1 and is provided as a way to eliminate the uncertainty engendered by imprecise knowledge of the control room envelope volume and to allow testing in CREs possessing a high value of makeup air flowrate.

3.2.1 CONSTANT FLOW TEST PROCEDURE

Tracer gas is injected into a CRE emergency ventilation supply duct at a rate calculated to achieve a desired concentration. For this test the target tracer gas concentration should lie in the middle of the measurement range of the gas analyzer.

An approximate value of the total air change rate is calculated based on a measured or assumed value of the makeup flowrate. This value, A_A, can be used to estimate the length of time that must elapse before concentration equilibrium will occur within the CRE. If one starts with a zero initial concentration and injects at a constant rate, it can be shown that the tracer gas will reach 95% of the equilibrium concentration within the CRE volume after a time equal to $3/A_A$.

Air samples from at least four spatially diverse locations within the CRE should be obtained at thirty minute intervals. Air samples must also be taken from the supply duct as well as the beginning and end of the return duct of the control room emergency ventilation system. For most conditions likely to be encountered in testing unfiltered inleakage, a maximum test duration of four hours should be used.

The total mechanical air supply flowrate (makeup plus recirculation) into the CRE should be measured using a pitot tube or hot wire traverse or a tracer flow technique.

3.2.2 CALCULATIONS

Tracer gas concentration data are treated by forming the mean of five measurements for each of the two concentration values, C_{sup} and C_r. The CRE Supply Rate is calculated by averaging the Pre and Post Test Supply Flowrates as follows:

$$Q_{sup} = (\text{Pretest Supply Flow} + \text{Post Test Supply Flow})/2 \qquad (10)$$

The unfiltered inleakage is then given by inserting these concentration values and flowrate into equation (8) to obtain Q_{in}.

3.3 DIRECT TRACER GAS INLEAKAGE TEST

Direct measurement of leakage (leak testing) using a tracer gas (usually helium and, less frequently, sulfur hexafluoride) is a powerful technique that is used extensively in the micro-electronics and defense/aerospace industries. In this technique, an object to be tested is either filled with tracer gas and the periphery monitored for leaking tracer, or the exterior is flooded with tracer gas and the interior is sampled for the presence of tracer gas. The measurement of non-zero quantities of tracer gas in either of these situations provides unambiguous evidence for the existence of leakage. The resulting tracer gas concentration can be used to infer leakage rate for a suitably designed experiment.

It is possible to apply this same reasoning to nuclear power plant CRE's. If one imagines a ventilated test volume surrounded by tracer gas as shown in Figure 13, leakage into the volume can be determined using conservation of mass. For this case;

$$Q_{in} = (C/C_0) \times Q_{makeup} \qquad (11)$$

where Q_{in} = unfiltered inleakage rate

Q_{makeup} = makeup flowrate

C = tracer concentration in CRE

C_0 = tracer concentration outside CRE.

In practice it is possible to challenge one boundary of the CRE at a time (if necessary for experimental convenience) with a concentration of tracer gas. Any tracer measured within the CRE would provide unambiguous evidence of inleakage through that boundary. Furthermore, by measuring the challenge concentration and the makeup flowrate within the CRE it is possible to calculate an inleakage rate across this boundary using equation (11) above.

An experimental complication to this technique is the potential for exhaust reentrainment to occur. If air containing tracer gas is exhausted from the CRE, it may reenter the CRE from the outside via the makeup fan. This reentrainment would render the results of any calculation based on equation (11) meaningless.

For those CRE's that possess filtered makeup air (i.e. filtered pressurization emergency ventilation system), it is possible to use a perfluorocarbon tracer and eliminate the possibility of reentrainment into the CRE. It has been documented that perfluorocarbon vapors exhibit exceptionally long hold-up times on carbon. Perfluordimethlycyclobutane (PDCB) exhibits at least thirty minutes hold-up in a nuclear industry standard two inch bed, while perfluoromethylcyclohexane (PMCH) exhibits a hold-up that is easily six times this value (Pearson et al., 1992). These vapors also possess a high detection sensitivity (approaching that of SF6) when analyzed using the techniques of electron capture gas chromatography.

Accordingly, if one were to challenge the exterior of a CRE with a moderate concentration of PMCH, one could sample inside the CRE for up to three hours without any concern about reentrainment of tracer gas. Measurement of PMCH within the CRE would provide unambiguous evidence of inleakage. Use of equation (11) above would allow a calculation of inleakage to be made.

For CREs that are wholly located within a plant building, it may be possible to seed the HVAC system that supplies the regions surrounding the CRE directly with tracer gas. Injection of a constant, known flowrate of tracer gas into the supply systems coupled with measurement of the resulting concentration in the regions surrounding the CRE would allow use of equation (8) to infer unfiltered inleakage.

Note that it is possible to use builders plastic (Visqueen) mounted on a lightweight wooden or metal framework to create a test volume surrounding some of the boundary walls of the CRE. This could be useful if one of the boundaries was, for instance, an outside wall or a roof. Mixing of the tracer gas within this plastic tent could be easily accomplished using several oscillating fans. The structure itself would not have to last longer than a few days. Using a combination of injection into rooms adjacent to the CRE and into fabricated plastic tents that enclose adjacent regions not contained within rooms, allows tracer inleakage testing to be performed on many CREs that rely on filtered pressurization during emergency operation.

3.3.1 DIRECT INLEAKAGE TEST PROCEDURE

Tracer gas is injected into the supply that provides ventilation air to the region surrounding the CRE (or into a specially fabricated plastic tent) at a rate calculated to achieve a desired concentration. For this test the target tracer gas concentration within the region(s) surrounding the CRE should be approximately 1 ppm. Anticipated concentrations within the CRE should lie in the middle of the measurement range of a second gas analyzer.

An approximate value of the total air change rate is calculated based on a measured or assumed value of the makeup flowrate. This value, A_A, can be used to estimate the length of time that must elapse before concentration equilibrium will occur within the CRE. If one starts with a zero initial concentration and injects at a constant rate, it can be shown that the tracer gas will reach 95% of the equilibrium concentration within the CRE volume after a time equal to $3/A_A$.

Air samples from at least four spatially diverse locations within the CRE should be obtained at thirty minute intervals. Air samples must also be taken from each region surrounding the CRE as well as on the delivery side of the charcoal filter in the control room emergency ventilation system. If significant breakthrough of tracer is detected at this point, the test must be terminated. For most conditions likely to be encountered in testing unfiltered inleakage a maximum test duration of three hours should be used.

The makeup flowrate supplied to the CRE should be measured using a pitot tube or hot wire traverse or a tracer flow technique.

3.3.2 CALCULATIONS

Tracer gas concentration data are treated by forming the mean of the final CRE concentration measurements and the final surrounding region concentration measurements to provide values of C and C_0 as required in equation (11).

The CRE Makeup Rate is calculated by averaging the Pre and Post Test Makeup Flowrates as follows:

$$Q_{makeup} = (\text{Pretest Makeup Flow} + \text{Post Test Makeup Flow})/2 \qquad (12)$$

The unfiltered inleakage, Q_{in} , is then calculated from equation (11).

4.0 CONCLUSIONS AND RECOMMENDATIONS

The preceding has provided a brief introduction to the principles of tracer gas ventilation measurements. Three different methods that allow assessment of unfiltered inleakage into a nuclear power plant Control Room Envelope (CRE) using

tracer gas techniques have been described. It has been shown that unfiltered inleakage within a CRE *can* be measured in a straightforward manner to better than +/- 10% in periods of less than eight hours.

The ability to measure actual inleakage in an operating ventilation system relates directly to the entire issue of safety and habitability of operating nuclear power plants during accident conditions as specified in GDC 19. An experimental method (or methods) to measure inleakage will result in more reliable estimates of Control Room Envelope integrity, and hence operator safety, in the event of a toxic gas release or radiological accident. The ability to reliably demonstrate the safety of control room occupants under accident conditions will provide immeasurable benefits both to the federal government and to the nuclear power generating industry.

5.0 ACKNOWLEDGMENT

This work was supported in part by a US Nuclear Regulatory Commission Small Business Innovation Research (SBIR) Grant, number NRC-04-94-070.

6.0 REFERENCES

Alevantis, L.E., and S.E. Hayward, "The Feasibility of Achieving Necessary Initial Mixing when using Tracer Gas Decays for Ventilation Measurements," in *Proceedings of the Fifth International Conference on Indoor Air Quality and Climate*, Toronto Canada, 1990.

American Society for Testing and Materials, ASTM Standard E779-87 "Standard Test Method for Determining Air Leakage by Fan Pressurization," Philadelphia, 1992.

--ASTM Standard E741-93 "Standard Test Method for Determining Air Change Rate in a Single Zone by Means of a Tracer Gas Dilution," Philadelphia, 1993.

Evans, R.G., and C.Y. Shaw, "A Multiposition Tracer Gas Sampling System for Building Air Movement Studies," in *AIVC Technical Note 24*, Air Infiltration and Ventilation Centre, University of Warwick, England, 1988.

Hayes, J.J., D.R. Moeller, and W.P. Gammill, "NRC Study of Control Room Habitability," in *Proceedings of the 18th DOE/NRC Air Cleaning Conference*, August, 1984.

Grot, R.A., and P.L. Lagus, "Application of Tracer Gas Analysis to Industrial Hygiene Investigations," in *Proceedings of the 12th Air Infiltration and Ventilation Centre Conference*, Ottawa, 1991.

Grot, R.A., and A.K. Persily, "Measured Infiltration and Ventilation Rates in Eight Large Office Buildings," in *Measured Air Leakage of Buildings*, ASTM STP 904, H.R. Trechsel and P.L. Lagus, Eds., ASTM, Philadelphia, 1986.

Hickey, E.E., G.A. Stoetzel, P.C. Olsen, and S.A. McGuire, "Air Sampling in the Workplace," *NUREG-1400*, USNRC, Washington, 1991.

Lagus, P.L., and A. Persily, "A Review of Tracer Gas Techniques for Measuring Airflows in Buildings," ASHRAE Trans. Vol. 91, 1985.

Lagus, P.L., V. Kluge, P. Woods, and J. Pearson, "Tracer Gas Testing Within the PaloVerde Nuclear Generating Station," in *Proceedings of the 20th DOE/NRC Air Cleaning Conference*, Boston, 1988.

Lagus, P.L., L. DuBois, K. Fleming, and J. Brown, "Control Room Inleakage Testing Using Tracer Gases at Zion Generating Station," in *Proceedings of the 22nd DOE/NRC Air Cleaning Conference*, Denver, 1992.

Moeller, D.W. and J.P. Kotra, "Commentary on Nuclear Power Plant Control Room Habitability," in *Proceedings of the 18th DOE/NRC Air Cleaning Conference*, August, 1984.

Murphy, K.G. and K. M. Campe, "Nuclear Power Plant Control Room Ventilation System Design for Meeting GDC 19," in *Proceedings of the 13th AEC Air Cleaning Conference*, August, 1974.

Pearson, J.P., K.M. Fleming, J.R. Hunt, and P.L. Lagus, "Replacement Tracer Agents for the In-place Testing of Adsorbers in NATS," in *Proceedings of the 22nd Doe/NRC Nuclear Air Cleaning and Treatment Conference*, Denver, 1992.

Persily, A.K., "Ventilation, Carbon Dioxide and ASHRAE Standard 62-1989," *ASHRAE Journal*, September, 1993.

Persily, A.K., and L.K. Norford, "Simultaneous Measurements of Infiltration and Intake in an Office Building," *ASHRAE Trans.*, Vol. 93, Pt. 2, 1987

Potter, N., J. Dewsbury, and T. Jones, "The Measurement of Air Infiltration Rates in Large Enclosures and Buildings," in *Air Infiltration Reduction in Existing Buildings*, proceedings of the Fourth Air Infiltration Centre Conference, Elm Switzerland, 1983.

Prior, J., J. Littler, and M. Adlard, "Development of Multi-tracer Gas Technique for Observing Air Movement in Buildings," *Air Infil. Rev.*, Vol. 4, No. 3, 1983.

Reardon, J.T., C.Y. Shaw, and F. Vaculik, "Air Change Rates and Carbon Dioxide Concentrations in a High Rise Office Building," *ASHRAE Trans.*, No. 100, Pt. 2, 1994.

Shaw, C.Y., J.S. Zhang, M.N. Said, R.J. Magee, and F. Vaculik, "Effect of Air Diffuser Layout on the Ventilation Conditions of a Workstation," *ASHRAE Trans.*, No.99, Pt.2, 1993.

Stage, S.A., "Computer Codes for Control Room Habitability (HABIT), NUREG/CR6210, US NRC, Washington, 1995

Vavasseur, C., "Application of Tracer Gas Methods to the Measurement of Ventilation Parameters in Nuclear Power Plants and Various Industrial Sectors," in *1st International Symposium on Ventilation for Contaminant Control*, Toronto, Canada, 1985.

Zuercher, C.H. and H. Feustel, "Air Infiltration in High-rise Buildings," in *Air Infiltration Reduction in Existing Buildings*, proceedings of the Fourth Air Infiltration Centre Conference, Elm Switzerland, 1983.

TABLE 2.1

TRACER GASES AND MEASUREMENT DEVICES

Techniques	Gases
Thermal Conductivity Detector	H_2, He, CO_2
Electron Capture Gas Chromatograph	SF_6, Refrigerants, Perfluorocarbons
Flame Ionization Gas Chromatograph	C_2H_6
Infrared Absorption Continuous Analyzer	CO, CO_2, SF_6, N_2O, C_2H_6, CH_4

TABLE 2.2

RELATIVE GAS COSTS
TAKING DETECTABILITY INTO ACCOUNT*

Gas	Detectable Concentration (ppm)	Maximum Measurable Volume per Dollar Ft^3	m^3
He	300	9.3×10^3	2.6×10^2
CO2	350**	3.2×10^4	8.9×10^2
N2O	1	2.8×10^6	7.9×10^4
SF6	5×10^{-6} (a)	5.6×10^{10}	1.6×10^9
SF6	1 (b)	5.6×10^4	1.6×10^3
CBrF3	5×10^{-5}	5.0×10^8	1.4×10^7
PDCB (c)	10×10^{-6}	1.3×10^9	3.7×10^7

* Based on 1994 Gas Prices for Size 1A Gas Cylinders. (1 Kgm liquid for PDCB)

** Average Background Concentration in the atmosphere.

(a) Detection by Electron Capture Gas Chromatography.

(b) Detection by Continuous IR Monitor.

(c) Perfluorodimethylcyclobutane

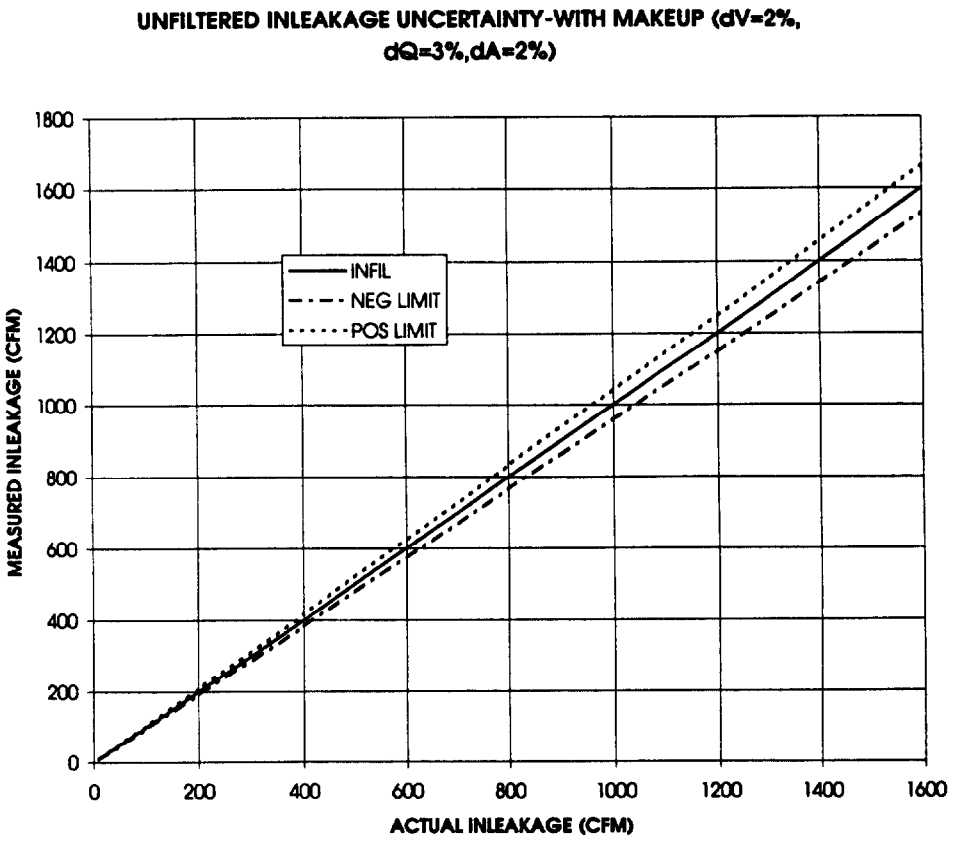

Figure 1. Unfiltered Inleakage with Makeup-Case I

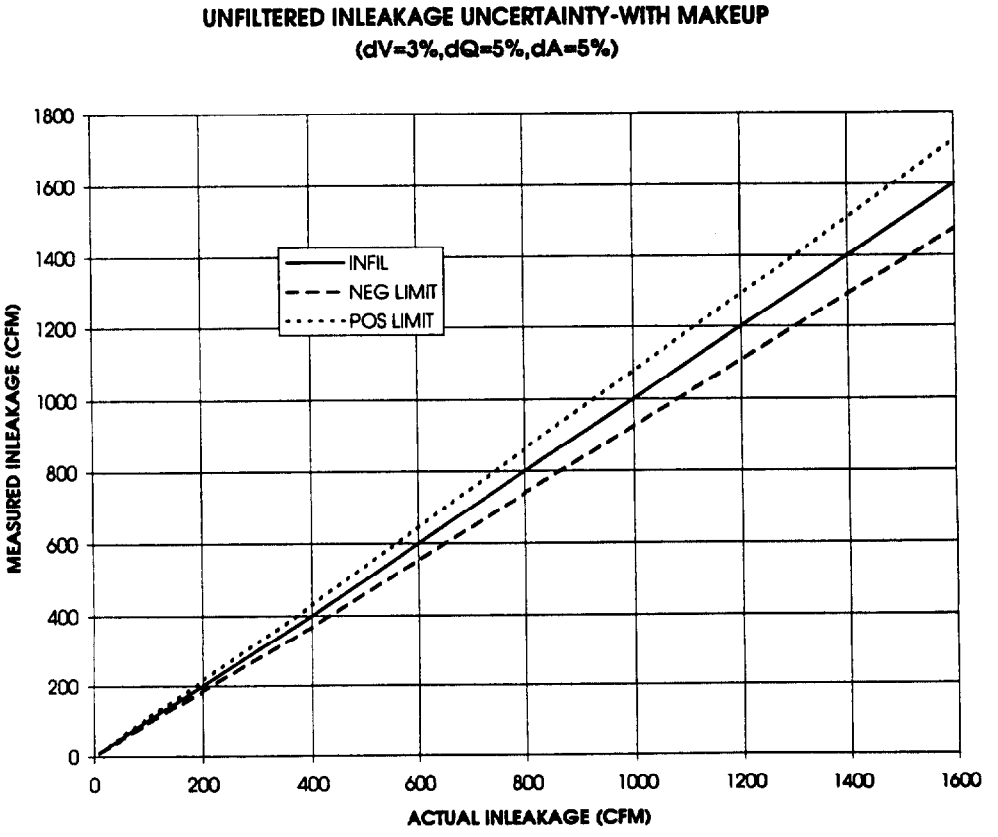

Figure 2. Unfiltered Inleakage with Makeup-Case II

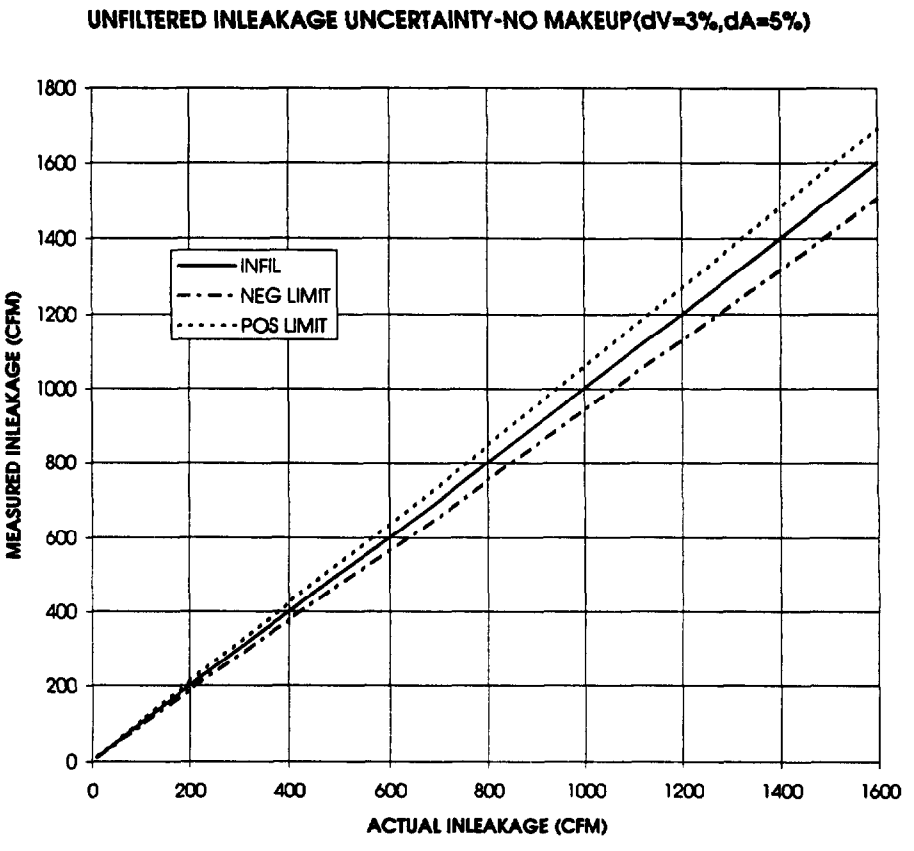

Figure 3. Unfiltered Inleakage no Makeup-Case III

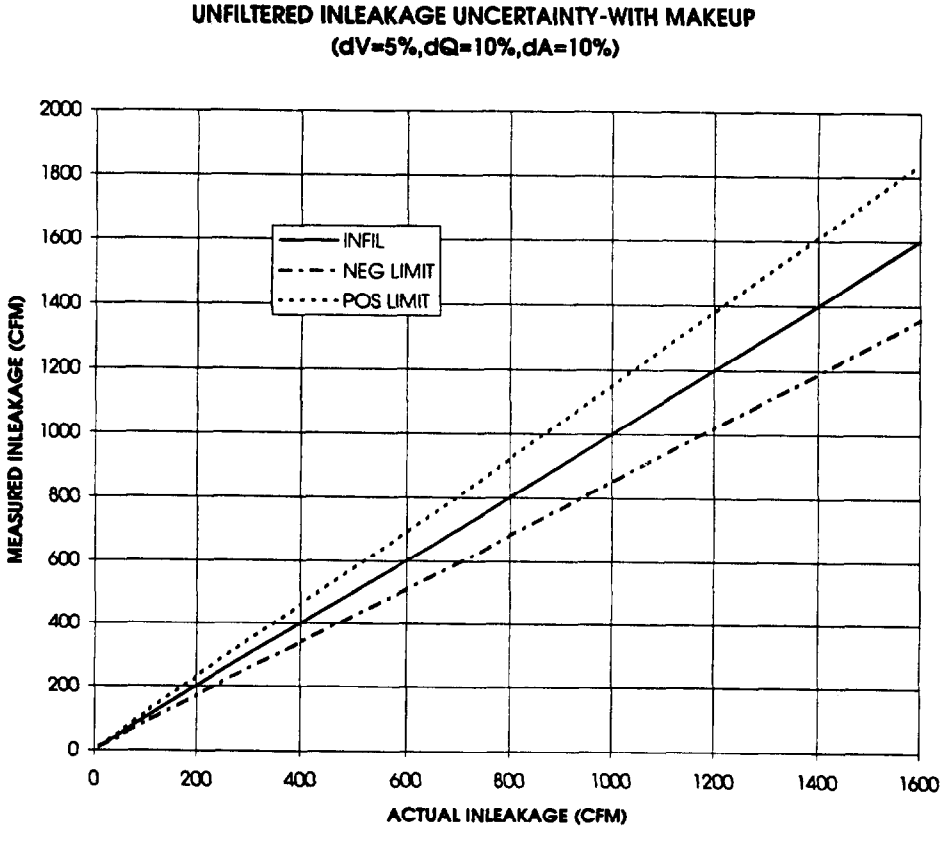

Figure 4. Unfiltered Inleakage with makeup-Case IV

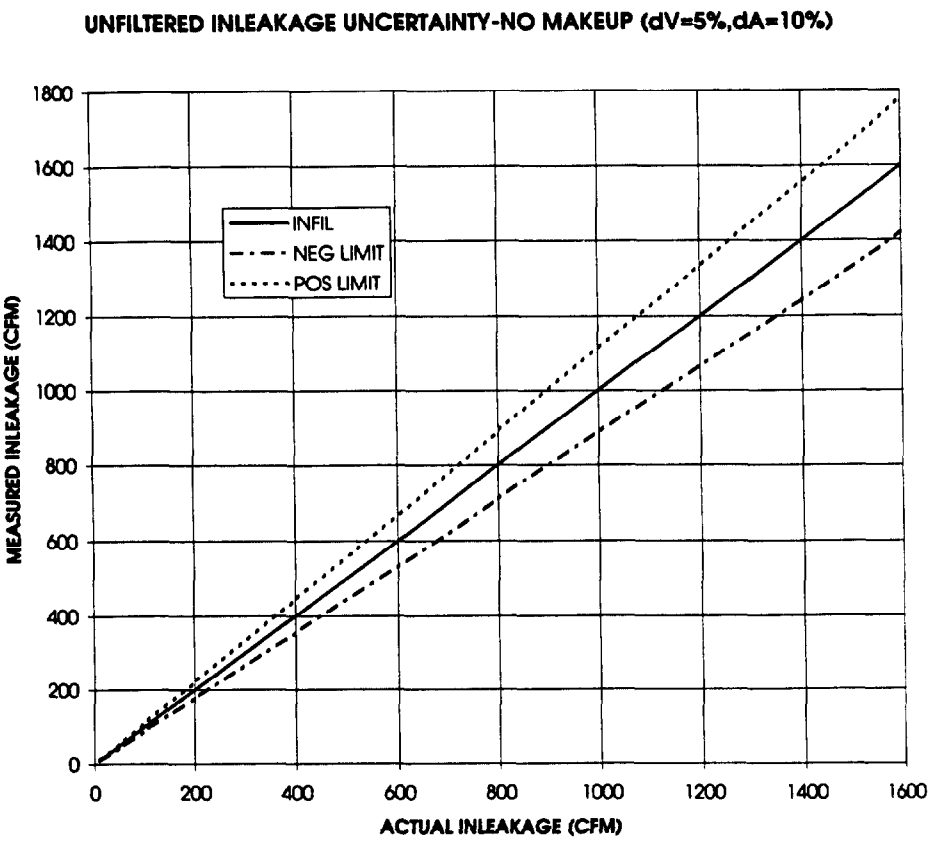

Figure 5. Unfiltered Inleakage no Makeup-Case V

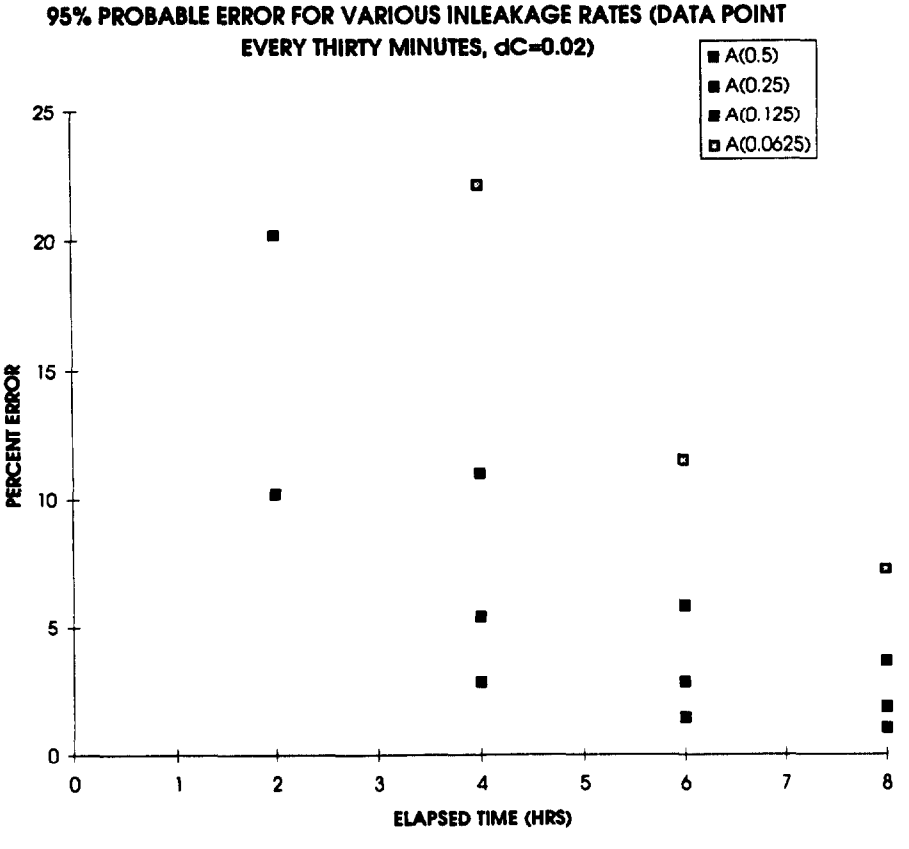

Figure 6. Probable Error-Data Point Every Thirty Minutes

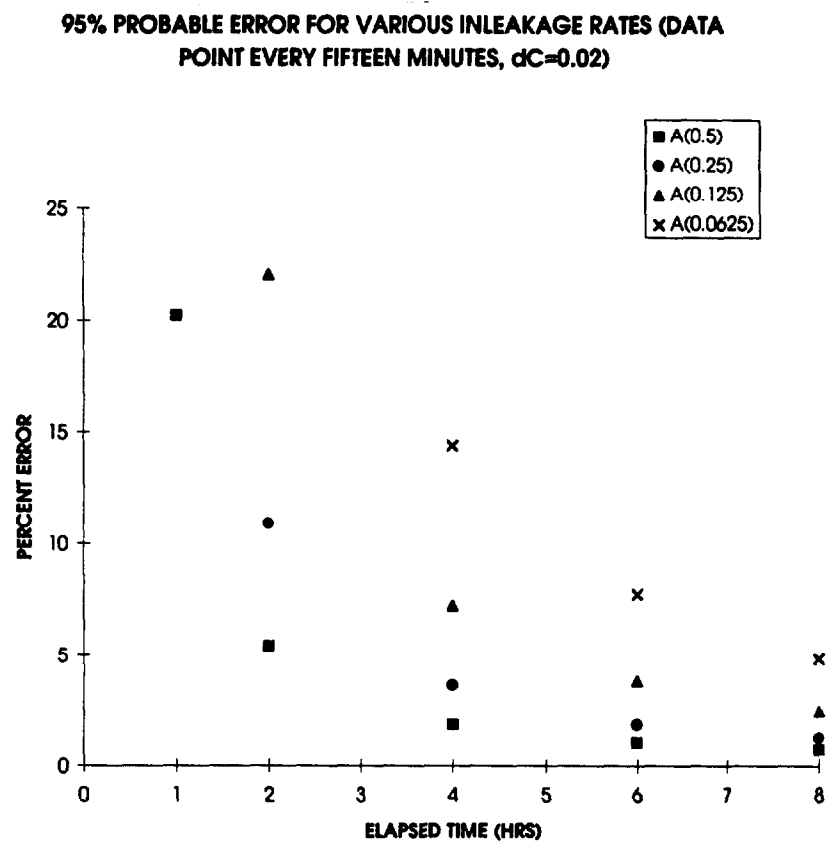

Figure 7. Probable Error-Data Point Every Fifteen Minutes

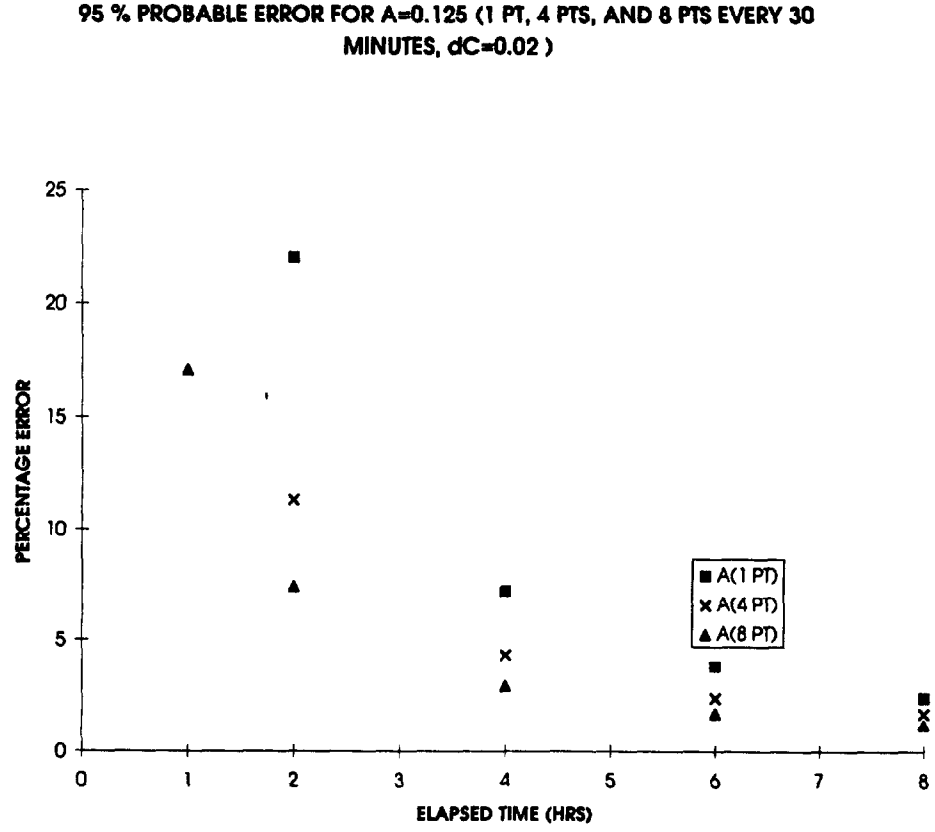

Figure 8. Probable Error-Multiple Points, dC=0.02

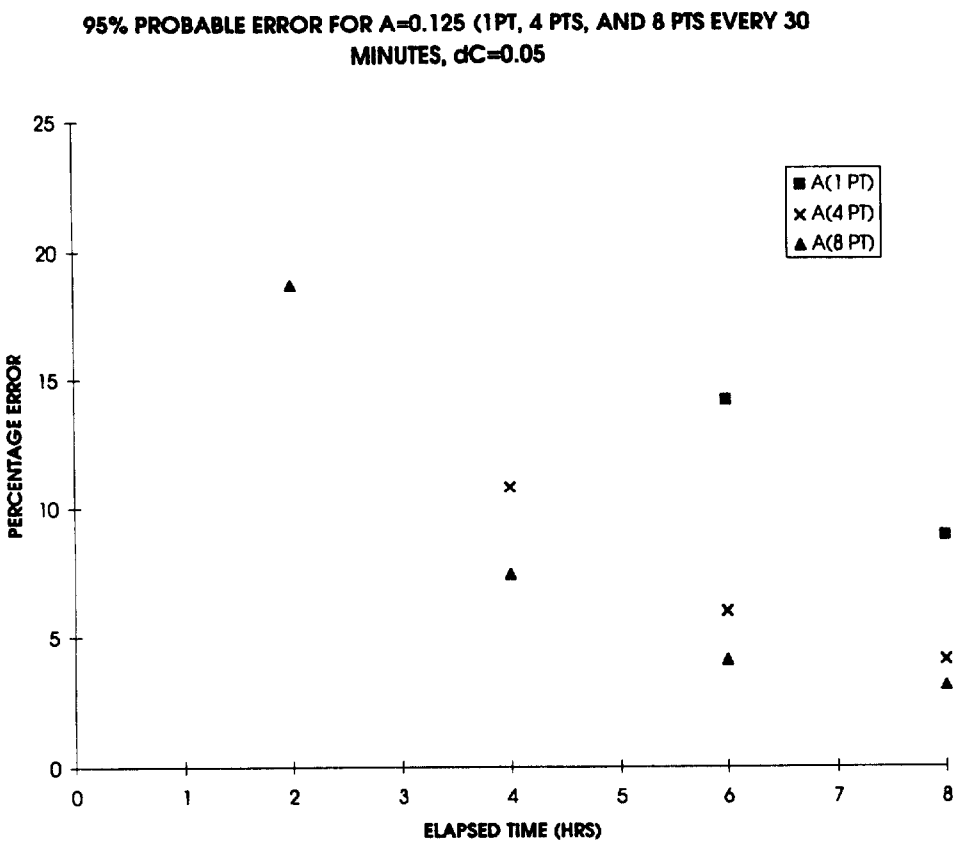

Figure 9. Probable Error- Multiple Points, dC=0.05

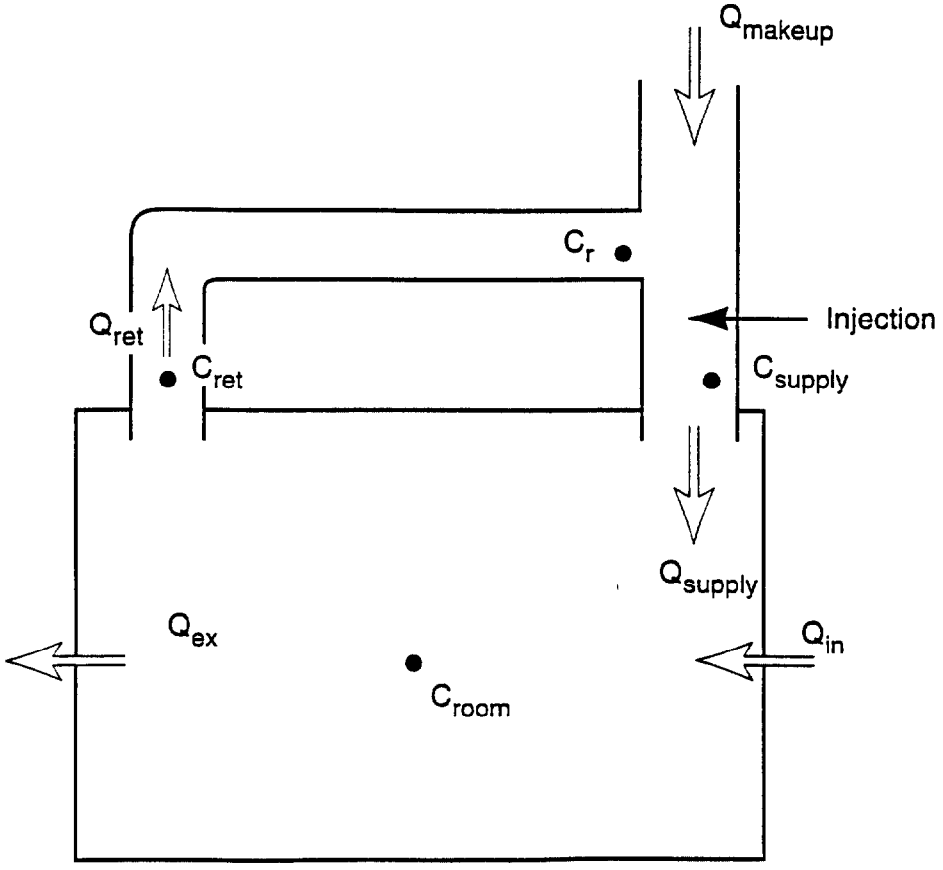

Figure 10. Control Room Envelope Test Parameters

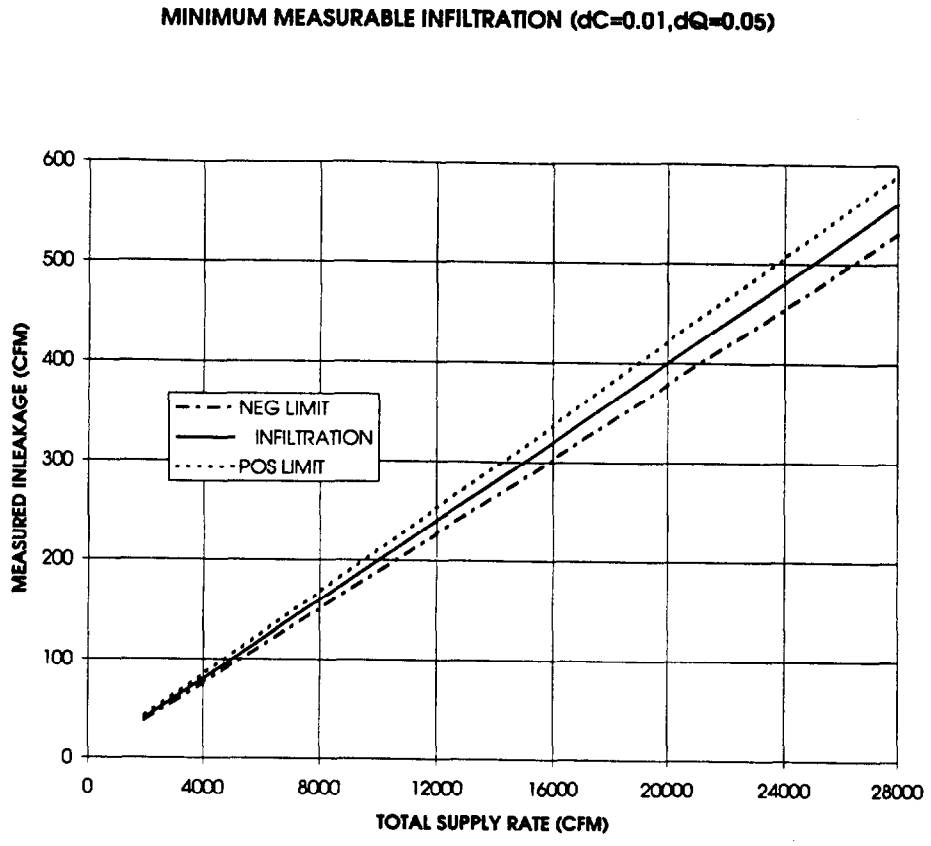

Figure 11. Minimum Measurable Inleakage, dC=0.01, dQ=0.05

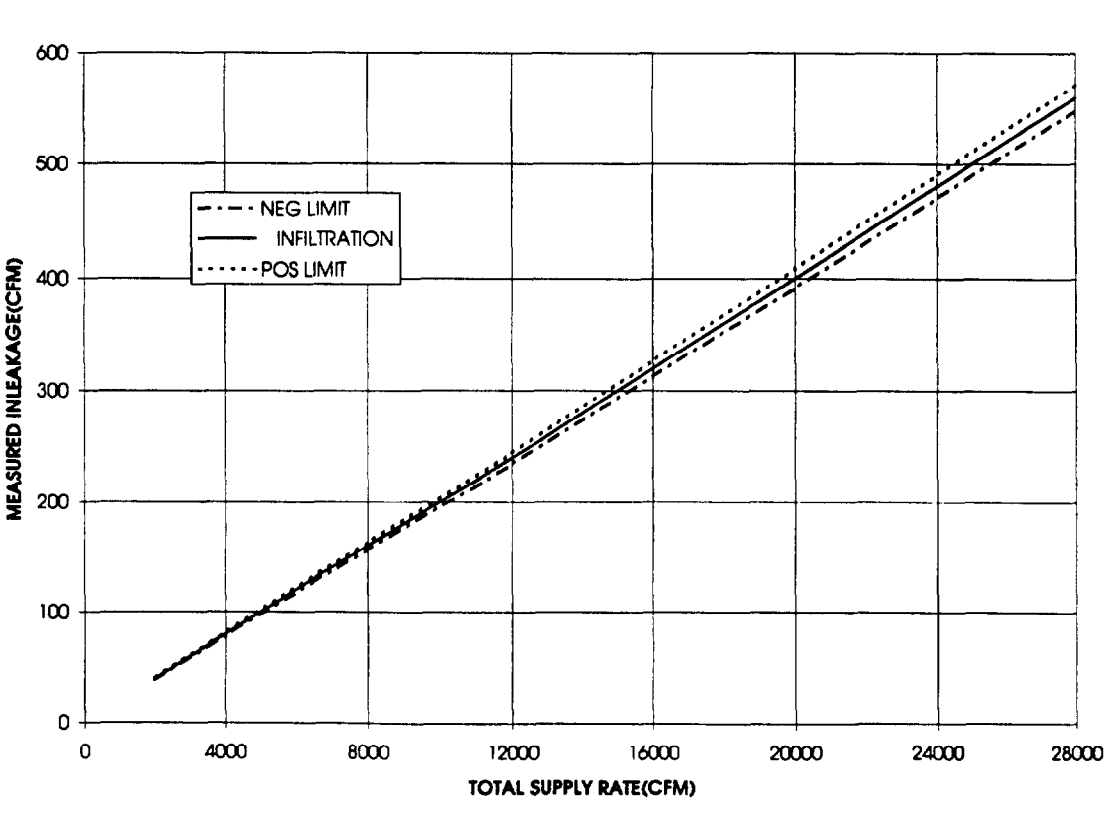

Figure 12. Minimum Measurable Inleakage, dC=0.005, dQ=0.02

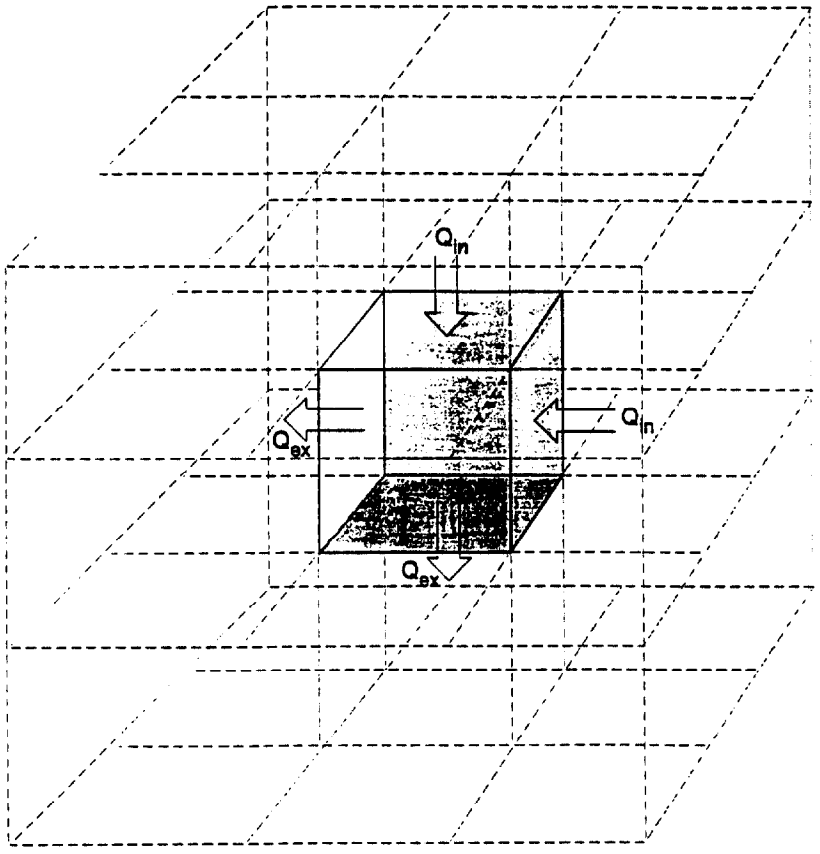

Figure 13. Control Room Envelope and Surrounding Regions

DISCUSSION

PORCO: I will exercise the chairman's prerogative and ask you a couple of very quick questions. How many control rooms has your protocol been applied to? How good was the data correlation? If you would, also mention how you achieved the good mixing that you mentioned in your paper.

LAGUS: We have done three plants, two systems in two of them and one in one of them including a control room. In terms of the uniformity test protocols, we were getting mixing of better than about 3%.

PORCO: What was your correlation between plants?

LAGUS: I do not understand what you mean by correlation between the plants.

PORCO: Was your inleakage consistent at different plants?

LAGUS: Very different from plant to plant.

PORCO: By about how much?

LAGUS: By a factor of six.

PORCO: The last part of my question was about mixing, how do you achieve good mixing of the tracer gas?

LAGUS: We achieved mixing by careful placement of the rather large twenty-four inch diameter mixing fans. We used six or eight of them in conjunction with the control room recirculation system to provide additional mixing. We would make measurements at a minimum of six or eight points at diverse locations and then run standard deviations on the numbers. In a single source control we were able to obtain mixing with relative standard deviations on the order of 3%. We did one at a two story control room where we got mixing of about 5%.

PHILIPPI: How does the control room leakage measurement protocol accommodate wind pressure changes from the outside, or pressure excursions in adjacent rooms? How do they affect the leakage of your control room?

LAGUS: On these tests we normally measure the control room envelope differential pressure between the inside and the outside, however that happens to be defined for a particular plant. Instead of accommodating, we basically measure it. What we are asking is, how does the system perform as it is being used? We have no control over the wind. What we have to do is be a) aware of the wind, b) be aware of the pressure characteristics, and then c) measure the performance of the system as it is being affected by the external variables. For instance, we try to minimize ingress and egress and things like that, but naturally occurring variables are the same variables that a plant is going to be subjected to. So, we are much more interested in finding out how it behaves under those circumstances than trying to make calculations or allowances for it. What you are going to find is that the effects of wind are certainly going to be a secondary effect, simply because, for most of the winds, you are not going to have wind pressures that are comparable to the kinds of pressures that one actually tries to generate inside a control room.

ENGELMANN: We know that there is in-leakage into ventilation systems when operating even in recirculation mode. Also, the air exchange of the room is enhoused with fans or recirculation are operating. Will you please discuss how you account for this?

LAGUS: The tracer technique incorporates all inleakage paths into the control room envelope (CRE), even those due to the CRE ventilation system, if that system or part of it is located outside the CRE boundary. Since the tracer technique allows one to measure the inleakage under actual operating conditions, if air exchange (unfiltered inleakage) is enhanced by operation of fans or recirculation, the data will reflect that. In fact we have undertaken a test in one control room in which the difference in inleakage was measured between the case of the pressurizing fan operating and not operating.