CONTROL ROOM AIR INLEAKAGE TESTING AT TWO NUCLEAR POWER PLANTS

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ABSTRACT

In the fall of 1996, both the Dresden and Quad Cities Nuclear Generating Stations began a program of air inleakage testing using tracer gas techniques. Since the Control Room Emergency Ventilation Systems provided makeup air for positive pressurization at both plants, a constant injection tracer gas test was utilized. The tracer gas testing disclosed that air inleakage rates were in excess of those allowed in the respective station FSAR analyses. Extensive sealing of both Control Room Envelopes was performed. Sealing of duct seams and penetrations, air handler and filter housings, wall penetrations, and in one case, the walls and ceiling of the Control Room, was required to reduce the air inleakage to an acceptable level. Retesting after completion of the sealing effort demonstrated that both plant Control Room Envelopes were within their original FSAR allowable inleakage rates.

1.0 INTRODUCTION

Increased regulatory skepticism concerning the adequacy of control room habitability analyses has prompted many nuclear utilities to reexamine in detail the assumptions underlying their analyses. The amount of unfiltered air entering the control room envelope is one of the critical assumed quantities. Until recently nuclear utilities could only rely on a variety of engineering models in order to arrive at a value for unfiltered air inleakage. These engineering models are based on crude and often incomplete assumptions about the nature of air flow through indoor spaces.

Research and development activities undertaken over the last twenty years for energy conservation studies and military defense evaluations produced a technology that uses tracer gas measurements to study the detailed performance of critical ventilation systems. Using this technology it is possible to quantify unfiltered air inleakage into an operating nuclear power plant control room (1,2).

In the fall of 1996, both the Dresden and Quad Cities Nuclear Generating Stations began a program of air inleakage testing using these tracer gas techniques. Since the Control Room Emergency Ventilation Systems provided makeup air for positive pressurization at both plants, it was possible to use a constant injection tracer gas test.

The constant injection tracer gas test used in these studies is an enhancement of the constant injection test described in a previous paper (2). As such it can be used to measure the total air inleakage into a mechanically ventilated space.

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 are successfully used in other areas of ventilation engineering and industrial hygiene to provide accurate characterization of HVAC performance under actual operating conditions (3,4).

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 (5,6). In the past few years tracer gas measurements designed to measure inleakage (either total or unfiltered) into a nuclear power plant control room have been accepted by the NRC and are often requested whenever questions arise regarding the performance or adequacy of nuclear power plant control room habitability systems.

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 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 E741-93 "Standard Test Method for Determining Air Change Rate in a Single Zone by Means of a Tracer Gas Dilution" (7). 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 method is an indirect method; i.e., it measures the equilibrium tracer concentration within a ventilated area. This concentration can be related to the air flow rate if the tracer release rate is known.

The constant concentration method is also an indirect method. It measures the amount of tracer as a function of time required to maintain a constant concentration within a ventilated zone or zones. The quantity of tracer injected can be related to the air flow rate. At present this is primarily a research method since the equipment required is more complex than that required for either the concentration decay or the constant injection test. It will not be described further in this proposal.

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 and instantaneously within the test volume, the mass balance equation is,

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

where V is the test volume, C(t) is the tracer gas concentration (dimensionless), dC(t)/dt is the time derivative of concentration, q(t) is the volumetric airflow rate out of the test volume, S(t) is the volumetric tracer gas injection rate, and t is time.

The air exchange or infiltration rate, A is given by A(t) = q(t)/V where A is in air changes per hour (h^{-1} or ACH). In the simplest case, the value of A represents the 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.

The unfiltered air inleakage testing at both the Dresden Nuclear Generating Station (NGS) and the Quad Cities Nuclear Generating Station (NGS) used the constant injection method. This method measures the equilibrium tracer concentration within a ventilated area. This concentration can be related to the air flow rate into the test volume if the tracer release rate is known.

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

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

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

As depicted in Figure 1, the tracer concentration initially increases with time but eventually reaches a plateau. After waiting a sufficient time (equal to approximately 3/A), the transient dies out and concentration equilibrium occurs.

Equation (2) then becomes the simple constant injection equation,

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

The results obtained with this technique are exact only when the system is in equilibrium, (i.e. concentration is not changing as a function of time). Otherwise, the results will be subject to errors, with the magnitude of these errors depending on the extent of the departure from equilibrium. All tracer concentration data used in the calculation of inleakage values in this paper were equilibrium values. Hence equation (3) could be applied.

In the air inleakage testing program at both Dresden and Quad Cities, the total air inflow rate into the CRE was measured using equation (3). A constant flowrate of tracer gas was injected into the supply side of the CRE ventilation system and, after waiting for concentration equilibrium to occur, a number of measurements of the resulting concentration at the most downstream (in terms of negative differential pressure) portion of the CRE system were obtained. Recasting equation (3) yields the following:

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

Where L_{tot} now represents the total air inflow into either the CRE. L_{tot} is made up of two components, namely, the amount of makeup air, $L_{m/u}$ and the amount of unfiltered inleakage, L_{unfilt} . C_{av} is the average concentration measured at the downstream point after concentration equilibrium has been obtained.

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

$$L_{tot} = L_{m/u} + L_{unfilt} \qquad (5)$$

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

$$L_{unfilt} = L_{tot} - L_{m/u} \qquad (6)$$

Since $L_{m/u}$ can be measured independently either by means of a pitot traverse or by using a tracer flow measurement technique, it is possible to calculate the total air inleakage into the CRE using equation (6). For the testing at both Dresden and Quad Cities, $L_{m/u}$ was measured using a tracer gas technique.

2.2 TRACER GAS FLOWRATE MEASUREMENT

For many years it has been known that a method to measure duct flowrates exists other than pitot tube or hot wire anemometer traverses. It entails the use of a tracer gas dilution method (8,9). 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. The rate of flow is readily calculated from the ratio of the tracer injection flowrate to the diluted concentration--in symbols:

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

The tracer gas method relies on the use of a tracer gas to infer flowrate through a section of duct. An individual flowrate 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 flowrate through the duct (as given by equation (7)). Thus, the measured concentration allows calculation of the flowrate since the injection flowrate is known.

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 flowrate.

In the following tables, the total uncertainty of each inleakage measurement is calculated using the prescription provided in ANSI/ASME Standard PT 19.1-1985 “Measurement Uncertainty” and represent 95% confidence limits. For the purposes of the uncertainty analysis, equation (8) is re-written as equation (9) to explicitly include all measured quantities.

$$L_{unfilt} = S * C_{inj} * [(1/C_{DS}) - (1/C_{m/u})] \qquad (9)$$

Equation (9) can be used in all uncertainty analyses to calculate statistically valid measures of uncertainty.

2.2 TRACER GAS & TRACER GAS MEASUREMENT TECHNIQUE

The large size of most nuclear power plant CREs influences the manner in which tracer gases are used and which gas analysis techniques are applied. Because of the (relatively) large volumes involved the quantity (and therefore the 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 detectable for a given analysis technique.

The fact that SF6, some halocarbon vapors, and some perfluorocarbon vapors can be measured to sub part per billion levels makes them a cost effective choice for testing within nuclear power generation facilities.

Detection of these gases and vapors is commonly undertaken using electron capture gas chromatographic techniques. Analysis of compounds using electron capture chromatography is a recognized analytical technique that was perfected in the 1970's for pesticide residue analysis. Using electron capture detection, concentrations of selected gases and vapors in the sub part per billion range can easily be measured if necessary.

In simplest terms, the gas monitors used in this study consist of a chromatographic separation column coupled to an electron capture detector. The chromatographic column operates to separate the various gaseous components of a sample by selectively slowing down some gases relative to others. The column can be thought of as a device to output the distinct components of a gas sample in a definite order. These components are then routed to the detector.

The electron-capture detector utilizes the high electron affinity of gases or vapors with halogen group elements to provide a measurable signal. SF6 is one such gas and exhibits a detection sensitivity on the order of a few parts per trillion (10^{-12}) when sensed with an electron capture detector.

In order to ensure the greatest possible measurement accuracy from the gas monitors, each channel of analyzer was individually calibrated immediately prior to each test. Calibration was effected by injecting into each analyzer three aliquots of a number of standard mixtures that spanned the anticipated concentration range. Resulting responses were recorded and then used to calculate a specific calibration curve for each analyzer. Note that daily individual calibration is standard analytical chemistry laboratory practice used for precision analyses of chemical constituents.

Calibration gas mixtures were obtained from a specialty gas supplier and analyzed to +/- 2% with traceability to NIST.

3.0 MEASURED INLEAKAGE VALUES

For both plants the emergency ventilation system provided filtered makeup pressurization with unfiltered recirculation. Thus, inleakage testing at both plants directly provided a measurement of *unfiltered* air inleakage. It should be noted that CRE Emergency Ventilation Systems in both plants included long runs of negative pressure duct work. These runs can contribute substantial amounts of inleakage into the CRE. Schematic illustrations of these Emergency Ventilation Systems are provided in Figures 2, 3, and 4.

At Dresden the CRE was taken as the Main Control Room (MCR) and the B-HVAC Equipment Room immediately adjacent to it. At Quad Cities, the CRE consisted of the Main Control Room, the Cable Spreading Room, the Auxiliary Electric Room, and the B HVAC Ventilation Room (known as the Dog House).

Tracer gas injection mixtures were obtained from an independent specialty gas supplier and were analyzed to +/- 1% with analyses traceable to NIST. Tracer gas injection was accomplished using an electronic mass flow controller in conjunction with a specially calibrated electronic mass flow meter.

In order to ensure the accuracy of the injection flow measurement. The electronic mass flow meters had previously been calibrated using a number of SF6 in nitrogen mixtures. The resulting data were used to corroborate the flow calibration equation provided by the manufacturer for use with gaseous mixtures.

In all tests, tracer gas injection continued for approximately five hours in order to assure that an equilibrium tracer concentration had been attained. Tracer gas sampling then commenced over an additional period of approximately three hours.

Within the various rooms of the Control Room Envelopes, air samples were taken directly as grab samples using disposable polypropylene syringes. Air samples from the ducts were obtained using a pump/manifold sampling system. Each sampling system consisted of a pump connected to a multi-position sampling valve. A Swage tee and septum fitting was affixed to the sample pump exhaust. This allowed remotely located air samples to be taken using polypropylene syringes. Lengths of polyethylene tubing were connected to the multi-position valve and were routed to the appropriate locations for sampling. All syringe samples were analyzed onsite for tracer gas concentrations.

Auxiliary mixing fans were placed in the Cable Spread, Auxiliary Electric and Dog House at Quad Cities to ensure good mixing of tracer gas. No mixing fans were used in either MCR as previous experience in other nuclear power plants has shown that the air flows into these well ventilated rooms are sufficient to mix tracer over the time interval that elapsed prior to initiation of sampling. It was experimentally determined that mixing fans were not required in the B HVAC Equipment Room at Dresden.

Measured unfiltered inleakage values are provided in Table 1 and 2 below. Note that in most cases several tests are reported since sealing of the CRE was an ongoing effort in conjunction with the inleakage testing. Techniques for actual leakage site detection and sealing are discussed in the next section of this paper.

4.0 LEAKAGE SITE DETECTION AND SEALING EFFORTS

Once it was determined that a slightly positive pressure between the CRE and any adjacent area was not being maintained during the normal ventilation lineup mode, the emergency ventilation mode lineup was checked at both the Dresden and Quad Cities Stations. The Control Room Ventilation System was placed in the emergency ventilation lineup and the differential pressure was then measured. At both stations it was determined to be less than the required +1/8 inch water gauge (in. w.g.) to all adjacent areas. Hence an extensive restoration effort was initiated at both stations. A detailed discussion of the sealing efforts undertaken at Dresden Station is provided in reference 10, which paper has been presented at this conference

4.1 INVESTIGATION PHASE

The inability to maintain the required differential pressure in the normal as well as the emergency ventilation lineups initiated the investigation phase. This phase was began with verification of the supply and return flowrates in an attempt to explain the inability to meet the differential pressure requirements. Once the supply and return airflows were demonstrated to be within expected parameters, the integrity of the CRE was suspect.

4.2 DISCOVERY PHASE

To confirm that the control room could be pressurized, return air dampers were closed to perform the initial CRE pressurization. It proved to be impossible to pressurize the CRE to the required 1/8 in.w.g. to all adjacent areas even with the return air throttled to its minimum. This failure to attain pressurization resulted in the initiation of the Discovery Phase of the CRE recovery process. It should be noted that at this point in the process, the failure to achieve requisite pressurization did not necessarily imply that the return air ductwork outside the CRE was leaking. We should also point out that as CRE leaks were identified and sealed the differential pressure increased. However, as the differential pressure increased some of these leaking areas again began to show evidence of leakage. This observation was often made apparent to the sealing team during the Restoration Phase.

The construction of the Dresden CRE was mostly painted concrete block walls covered by wallboard in the MCR. As such, the envelope exhibited considerable leakage throughout its entire area. The Quad Cities CRE primarily consisted of poured concrete walls. These proved to be less prone to exhibit leakage.

Nearly 200 leaks were discovered at both the Dresden and Quad Cities Stations in electrical consoles that incorporate floor penetrations connecting the MCR to adjacent areas outside the CRE. At Dresden, additional leakage sites were discovered behind the wallboard covering in the MCR. This discovery required removal of the wallboard. Upon removal numerous cracks in the block wall construction as well as unsealed metal partitions were observed. These cracks and unsealed metal partitions were filled during the initial discovery phase. Penetrations of less than one inch that were not sufficiently considered for Appendix R were leak checked and sealed as required. Floor and ceiling joint lines at the MCR walls disclosed several regions of substantial cracking. These cracks were subsequently sealed.

In the case of Quad Cities, a part of the CRE (the B Mechanical Room, known as the Dog House) was not physically adjacent to the MCR. This room was found to be leaking at similar locations as described in the above paragraph. Sealing was also effected at fan shaft seals and in locked seam ducting. All return ductwork joints and longitudinal seams were sealed methodically to ensure that no leakage contribution remained.

CRE differential pressure was measured daily following key sealing events in order to track the progress of the sealing effort. As discussed above, as the sealing effort progressed and the CRE differential pressure increased additional leaks appeared that required sealing. The delayed appearance of leakage sites required several leak sealing teams working in parallel. This requirement proved to be very costly and time consuming based upon the resources needed for continuous leak detection and sealing.

At Dresden, key isolation damper leakage was also suspected as this leakage could decrease the impact of other sealing efforts on the attainment of suitable differential pressure. Damper leakage can be measured by conventional pressurization techniques as well as tracer gas techniques. At Dresden tracer gas tests were undertaken on all critical isolation dampers (Y). Standard repair methods were undertaken such as damper blade repair and/or replacement.

4.3 RECOVERY PHASE

Once incremental pressure increases were realized, certain recovery of CRE integrity was underway. During this phase CRE differential pressures of up to 0.4 in. w.g. were noted, but upon discovery and subsequent sealing of leakage sites in the return ducting, the CRE differential pressures often returned to near neutral values. This phenomenon was indicative that further significant leakage sites existed in the CRE which required discovery and sealing. It is important to point out the existence of a suitably high value of CRE differential pressure *does not ensure* that significant inleakage into the CRE is not occurring, for instance, from leakage sites in the return ductwork and the return air handling unit housings.

Additional leak detection efforts disclosed that large leaks were occurring in numerous cable tray penetrations and hard to reach CRE ceiling areas. Subsequent sealing of these leakage sites resulted in the attainment of the required 1/8 in. w.g. to all adjacent areas. Surveillance and preventative maintenance actions were established to maintain of the CRE on a routine basis.

4.4 LESSONS LEARNED

- Understand the design and licensing basis for CRE Habitability
- Challenge the CRE to verify that the boundary can be pressurized by throttling the return air damper (or other means) prior to undertaking other remedial efforts.
- Once it is demonstrated that the CRE possesses significant leakage sites, form one or more sealing teams to immediately begin sealing obvious leakage sites using visual observations, common sense, and smoke pencils. This will conserve resources. At a minimum these teams should be overseen by an experienced sealing vendor.
- Perform sealing efforts in Mode 1 as much as practicable using approved sealing details.
- To establish a baseline, undertake quantitative inleakage testing using tracer gas techniques.
- Continue to seal the CRE in parallel with other operations.
- Seal all ductwork joints, especially return ductwork joints using hard cast or other approved methods. Note that this may require an extensive scaffolding effort.
- A sealing team with experience proved invaluable in terms of cost effectiveness and timely completion of sealing efforts.
- Keep an updated dose calculation with the most limiting accident using the most current criteria to support any assumptions made in the calculation

Returning the CRE to its required operating conditions required a team effort. An experienced team that incorporates leak detection, leak sealing, tracer testing, and air balancing expertise is required to create a true success path.

5.0 CONCLUSIONS

After a substantial sealing effort, both Control Room Envelopes were restored to their design values of unfiltered inleakage. The constant injection tracer gas technique allowed the progress of the sealing efforts to be tracked and provided quantitative feedback to the sealing teams.

The constant injection tracer technique has proven itself useful for measuring inleakage on CRE Emergency Ventilation Systems that provide makeup air in order to pressurize the CRE during an event. The technique provides a direct measure of inleakage independent of any engineering assumptions about leakage sites and leakage areas.

In addition, for those systems in which it is possible to simultaneously measure makeup flowrate with a tracer technique, a complete, statistically valid uncertainty analysis can be performed. This has the added benefit that uncertainties are quantitatively addressed in a statistical manner and do not rely on engineering judgment for their interpretation.

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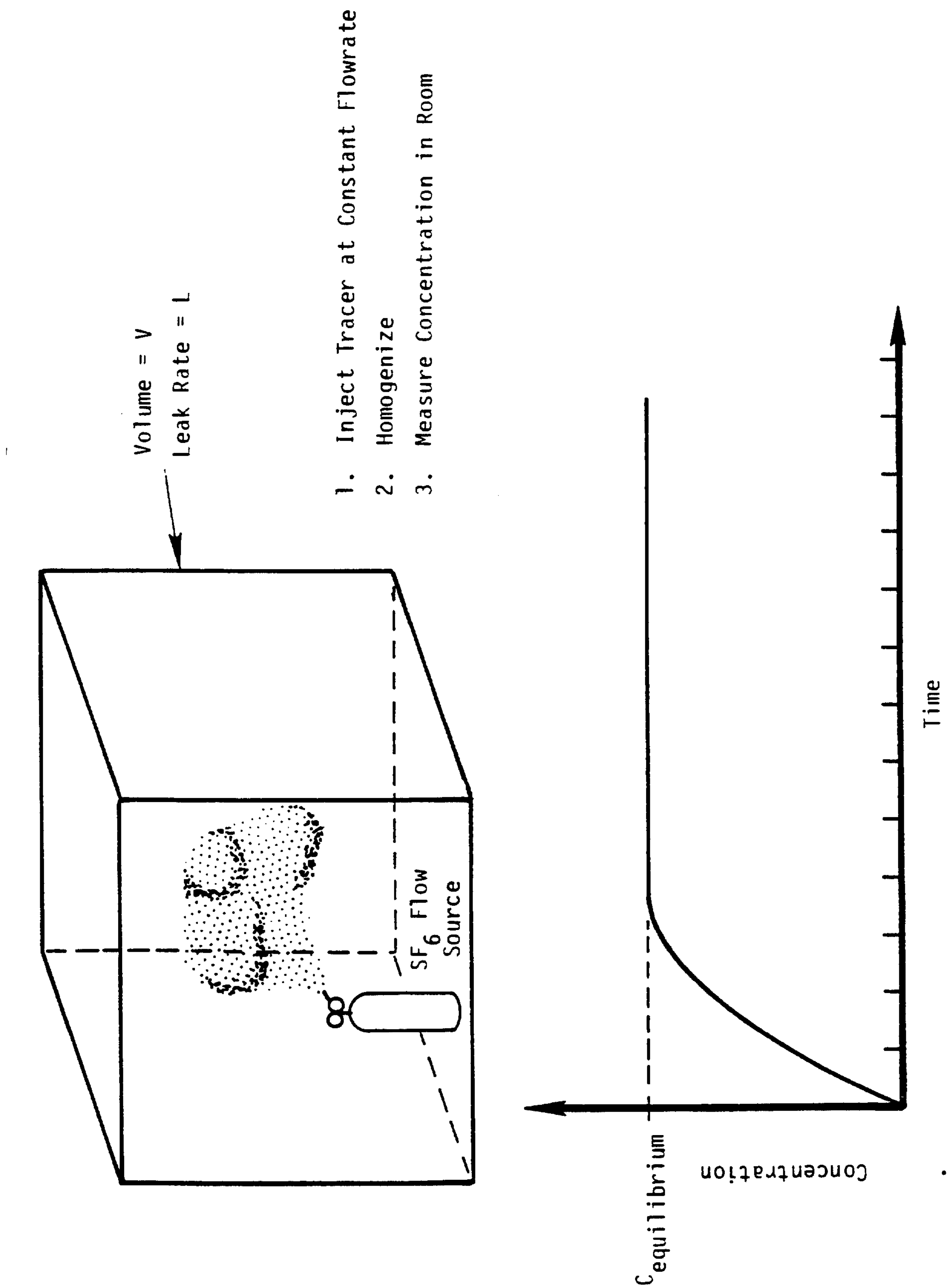

Figure 1. Concentration buildup in test volume as function of time.

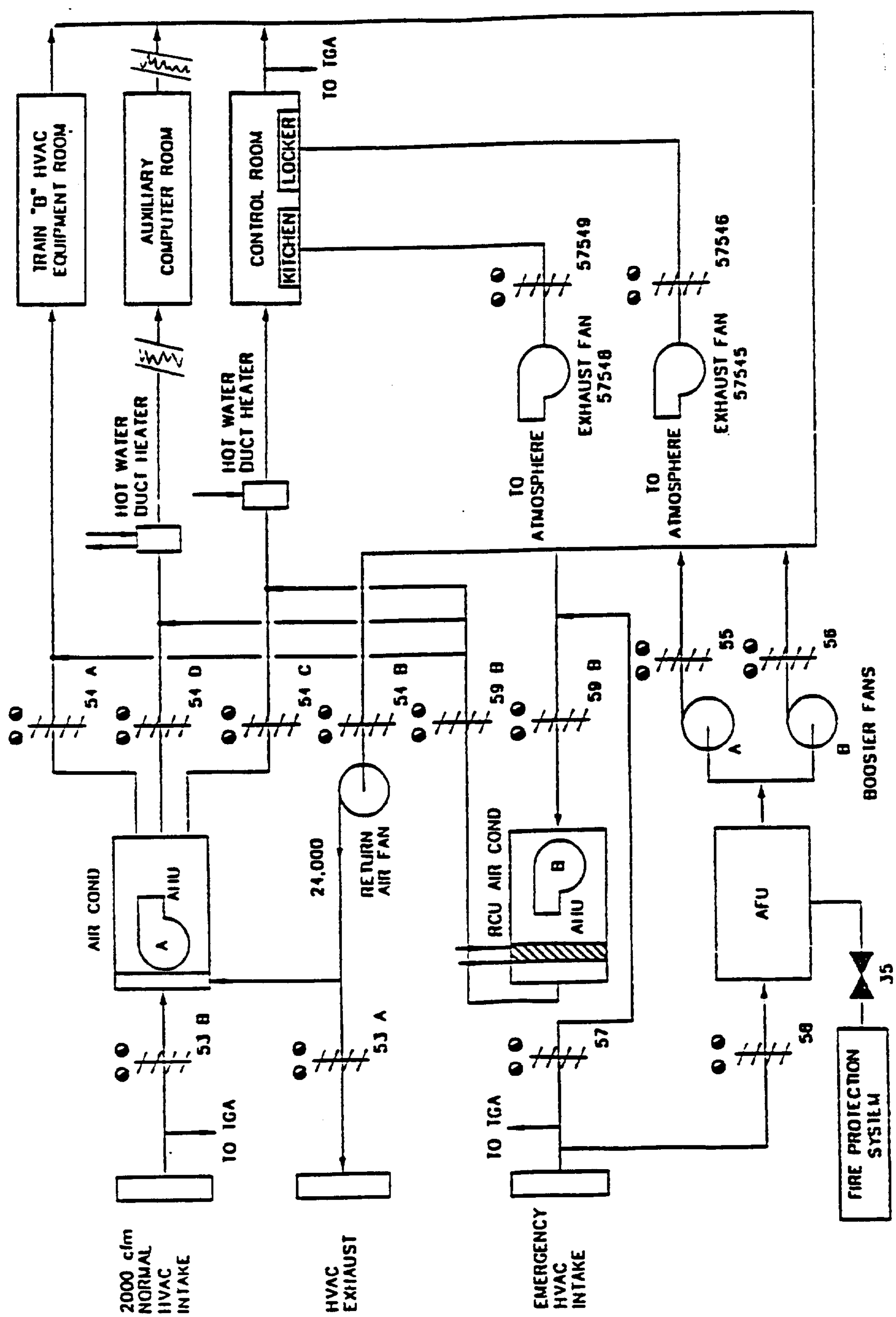

Figure 2. Dresden CRE Emergency Ventilation System

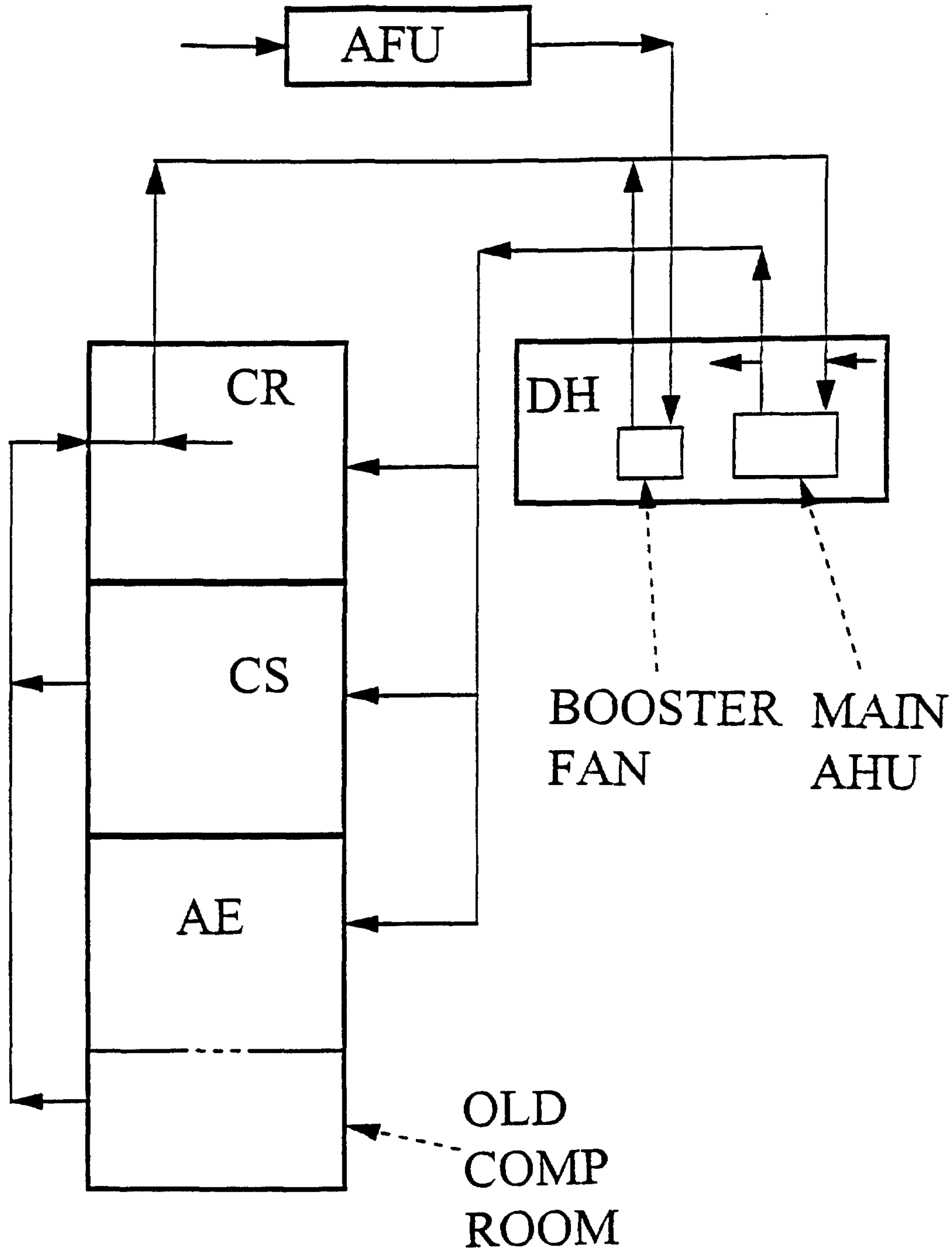

Figure 3. Quad Cities B Train CRE Emergency Ventilation System

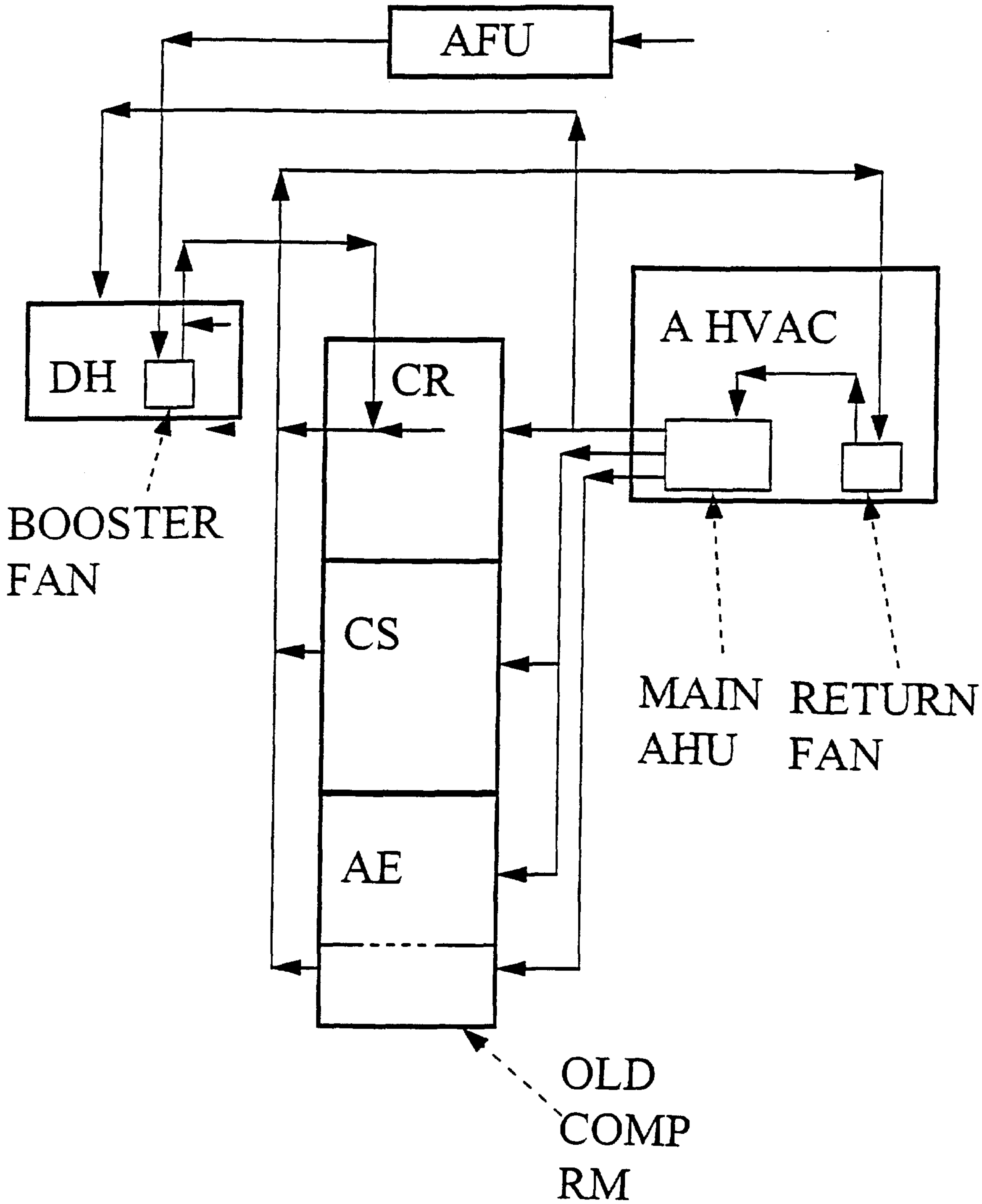

Figure 4. Quad Cities A Train CRE Emergency Ventilation System

Table 1

Dresden Inleakage Data

DATE	SYSTEM	INLEAKAGE (SCFM)
10/14/96	B	712*
10/18/96	B	4056
10/20/96	B	437 +/- 81
1/8/97	A	341 +/- 91
1/9/97	B	156 +/- 86
1/9/97	A	294 +/- 87
1/10/97	A	228 +/- 88
1/11/97	A	162 +/- 91

* Leakage for MCR only, B HVAC Room Isolated for this test .

Table 2

Quad Cities Inleakage Data

DATE	SYSTEM	INLEAKAGE (SCFM)
11/2/96	B	273 +/- 99
4/8/97	A	186 +/- 93
4/19/97	A	222 +/- 55
4/22/97	B	88 +/- 62