BNL-69105
INFORMAL REPORT

MULTI-TRACER CONTROL ROOM AIR INLEAKAGE PROTOCOL AND SIMULATED PRIMARY AND EXTENDED MULTI-ZONE RESULTS

R. N. DIETZ

January 2002

ENVIRONMENTAL SCIENCES DEPARTMENT

BROOKHAVEN NATIONAL LABORATORY
UPTON, LONG ISLAND, NEW YORK 11973

DISCLAIMER

BNL-69105
Informal Report

MULTI-TRACER CONTROL ROOM AIR INLEAKAGE PROTOCOL AND SIMULATED PRIMARY AND EXTENDED MULTI-ZONE RESULTS

Russell N. Dietz, Head
Tracer Technology Center
Brookhaven National Laboratory
Upton, New York 11973-5000

A Concept Paper

For discussion with
the Nuclear Power Plant Industry

January 2002

Research by BNL investigators was performed under the auspices of the U.S. Department of Energy under Contract No. DE-AC02-98CH10886.

ABSTRACT

The perfluorocarbon tracer (PFT) technology can be applied simultaneously to the wide range in zonal flowrates (from tens of cfms in some Control Rooms to almost 1,000,000 cfm in Turbine Buildings), to achieve the necessary uniform tagging for subsequent determination of the desired air inleakage and outleakage from all zones surrounding a plant's Control Room (CR). New types of PFT sources (Mega sources) were devised and tested to handle the unusually large flowrates in a number of HVAC zones in power stations. A review of the plans of a particular nuclear power plant and subsequent simulations of the tagging and sampling results confirm that the technology can provide the necessary concentration measurement data to allow the important ventilation pathways involving the Control Room and its air flow communications with all adjacent zones to be quantitatively determined with minimal uncertainty. Depending on need, a simple single or 3-zone scheme (involving the Control Room alone or along with the Aux. Bldg. and Turbine Bldg.) or a more complex test involving up to 7 zones simultaneously can be accommodated with the current revisions to the technology; to test all the possible flow pathways, several different combinations of up to 7 zones would need to be run. The potential exists that for an appropriate investment, in about 2 years, it would be possible to completely evaluate an entire power plant in a single extended multizone test with up to 12 to 13 separate HVAC zones. With multiple samplers in the Control Room near each of the contiguous zones, not only will the prevalent inleakage or outleakage zones be documented, but the particular location of the pathway's room of ingress can be identified. The suggested protocol is to perform a 3-zone test involving the Control Room, Aux. Bldg., and Turbine Bldg. to 1) verify CR total inleakage and 2) proportion that inleakage to distinguish that from the other 2 major buildings and any remaining untagged locations. These results would then direct the next subsequent tests. Final results would point to where mitigation steps should be initiated. Protocols for repeat testing as well as long term continual testing are suggested.

Introduction

Control Room (CR) habitability is an important design consideration for the nuclear power industry. A significant element of habitability analyses is unfiltered air inleakage which could potentially carry entrained toxic and/or radiological contaminants into the Control Room. Brookhaven's perfluorocarbon tracer (PFT) technology(1) has been determined to be an acceptable method for quantifying the unfiltered air leakage as a whole and identifying the specific pathways of communication between the CR and surrounding areas. The technology has been applied to multizone air inleakage and air exchange measurements for more than 20 years(2). Critical for the CR issue is the ability to not only quantify those flow rates, but also to assess the magnitude of the uncertainty in those determinations.(3)

The purpose of this document is two-fold – 1) to present the approach that will be used to technically tag the various primary and secondary air handling systems (HVACs) and sample the interior air for steady state tracer concentrations, and 2) to provide an example of primary and secondary air inleakage calculations for converting measured tracer concentrations into air inleakage and exchange rates and their uncertainties.

The *primary flowrates* are:

1. Total CR inleakage and uncertainty, and
2. Partitioned in leakage from the Auxiliary Building (AB), the Turbine Building (TB), and from other untagged areas including directly from outside (if any) and those uncertainties.

Generically, almost all 100 plus facilities in the US will be applicable to the primary-objective approach.

The *secondary flowrates* to be quantified will provide a clearer understanding of specific pathways of inleakage, which could facilitate mitigating strategies if air inleakage or exchange is excessive, especially from critical areas. Mitigating techniques may include sealing identified pathways or rebalancing ventilation flows to reduce differential pressures across the barrier of concern. The exact description of secondary areas or zones of air exchange will depend on the particular nuclear power station, but could include air exchange between:

1. Component Cooling Pump Room (CCPRs) and Cable Spreading Rooms (CSRs),
2. TB and CR via specific vestibules or doorways at several elevations,
3. CRHVAC equipment rooms and adjacent non-envelope hallways, offices, and equipment rooms, and between
4. CR envelope and Switchgear rooms (SWGRs), Main Steam Isolation Valve (MSIVs) rooms, and battery rooms (BRs).

Suggested locations for tagging and sampling in the primary (Control Room, Auxiliary Building, and Turbine Building) zones (1, 2, and 3, respectively) will be described using the nomenclature of a specific nuclear power plant, serving as a pilot facility. Simultaneously, with the 3-zone testing, up to 4 additional zones can be accommodated at this time; tagging and sampling recommendations for 4 of the 6 to 8 other secondary inleakage locations have been provided. Several repeated testings will allow all zonal inleakages to be documented. In one to two years, a new analysis system, new purified tracers, and refined software will allow up to 12 to 13 zones to be handled simultaneously.

Appendix A section provides results from an assumed distribution of air inleakages based on a total CR inleakage of 3000 cfm from previous SF_6 decay measurements at the pilot facility; the predicted multitracer concentration matrix was then used to recompute the assumed flowrate distribution – but now with their expected uncertainties as well. Appendix B broadens the number of zones from the 3 primary to a total of 7, including examples of secondary locations discussed on the previous page.

Tagging and Sampling the 3 Primary Zones: Control Rm, Aux Bldg, and Turbine Bldg

Tagging - PFT tagging is accomplished with small devices about the size of an eraser on a pencil (a regular source) to the size of a large thimble (a "Mega" source), about the size of the first digit of one's thumb. Typically, in buildings with HVAC systems, the PFT source(s) are deployed at the supply air (SA) side where the actual temperature of the temperature-dependent sources is known. Because of the high flow rates of typically 50,000 cfm per fan associated with power plants, "Mega" sources were recently developed for this project, having source strengths about 100-fold higher than regular sources. The resulting tagged steady state concentrations of 1 to 10 parts per trillion (ppt or pL/L or nL/m^3) are overall 10s- to 100s-fold lower than the current ambient background of the previously common refrigerants, R-11 and R-12. The safe use of the perfluorocarbon tracers and their environmentally benign nature have been documented[4, 5].

The expected tagging quantities for the 3 primary systems are:

Table 1. Tagging Control Room, Auxiliary Building, and Turbine Building

		"Mega" Sources			
Zone	Location	Qty.	Rate, µL/h	Type	Expected Conc., ppt
1	Control Room – 3,000 cfm inleakage (1 circfan @ 45,000 cfm)	1	48	ptPDCH	9.4
2	Auxiliary Building (2 SA fans @ 50,000 cfm each)	4	720	PMCP	4.2
3	Turbine Building (12 SA fans @ 50,000 cfm each)	12	2,304	PDCB	2.2

The Auxiliary Building will be tagged with 2 “Mega” sources at each of the 2 SA fans. Since these provide once-through outside air, the sources may be placed in a conditioned, known-temperature location. The 12 Turbine Building fan locations will reflect mainly outside temperature conditions which could be monitored to know the source strength to within ±10%; a source increases its rate about 2% per °F increase.

The Auxiliary Building and Turbine Building PFT “Mega” sources are the most volatile and will last for about 1 year if they are freshly prepared; the other sources will last from 2 to 5 years.

Sampling - The passive sampling tube(2) is a glass tube (CATS) about the size of a cigarette. The equivalent sampling rate of about 0.2 liters of air per day and the expected PFT concentration would suggest a sampling duration of about 1 day. Several days or several weeks of a single integrated measurement period would be fine. With Brookhaven’s newest GC system, even a few hours sampling period would be adequate; less than a few hours is not recommended.

Initially, a greater number of samples will be used in order to arrive at the best representative locations for subsequent sampling tests. Table 2 lists the suggested sampling locations in the 3 primary zones. Many of the proposed 13 sampling locations in the Control Room look at local ventilation effects. For example, the 2 CATS in the 69′ CR Equip. Rm. would see tracer from the Access Control SA if inleakage occurs there. The CATS in each of the CR Computer Rms would see inleakage from the SWGRs. The overall computed flow rates would use the average of concentrations from all CATS locations; but the localization of the point of inleakage from (or outleakage to) a particular nearby zone would be indicated by the local CATS. Similarly, placement of extra CATS in the Aux. Bldg. and along the Turbine Bldg. “K” wall were selected for detecting local ventilation pathways.

The 3 PFT types (Table 1) and the 41 CATS (Table 2) will allow adequate determination of:

1. Total CR air inleakage and uncertainty, and
2. The air inleakage pathways from the Auxiliary Building, the Turbine Building, and elsewhere.

A review by plant personnel should be made of suggested locations and critiqued to reach the best distribution. At the conclusion of the first few tests, it is expected that the number of samplers can be reduced 3-fold, to about 12 to 15 total, for any necessary subsequent tests or for periodic routine testing.

Turbine Building (TB) and Initial Quantity of Samplers (CATS)

Zone	ID	Elev.	Room (Rm)	Location	CATS Qty.
1	CR	69_	CR Equip. Rm	East & west sides	2
		56_	Tech Support Rm	Center	1
		56_	Central Alarm Station	Center	1
		45_	CR Annex	Center	1
		45_	CR Proper	North & south sides	2
		45_	Comp Rm Unit 1	Center	1
		45_	Comp Rm Unit 2	Center	1
		27_	Cable Spreading Rm Unit 1	East & west sides	2
		27_	Cable Spreading Rm Unit 2	East & west sides	2
				Sum =	13
2	AB	69_	Main Plant Exh. Eq. Rms (2)	Center of each	2
		69_	Personnel Air Lock Areas (2)	Center of each	2
		45_	Piping Areas & Passage (3)	Center of each	3
		27_	Passage 308	North & south ends	2
		5_	Comp. Cooling Pump Rms (2)	East & west ends	4
				Sum =	13
3	TB	56_	Along "K" wall	?	--
		45_	Along "K" wall	@3, 13, 23, 32, 42, 48	6
		27_	Along "K" wall	@3, 13, 22, 32, 42, 48	6
		5_	Along "K" wall	@3, 24, 48	3
				Sum =	15
			Grand Sum = 41 CATS		

Typical Expected Primary 3-zone Results

Appendix A provides the full details of the type of results that will be generated in any power plant station testing. Although the testing cited was for expected observations for the pilot facility, the magnitudes of the uncertainties in the results were confirmed to be typical of almost all results over the past 20 years in a range of facilities. It is safe to conclude that the following uncertainties should be applicable at all nuclear stations:

Control Room Inleakage	Uncertainty
Total	±7 to 12%
From Aux. Bldg.	±11 to 16%
From Turbine Bldg.	±14 to 20%
From Untagged Locations	±20 to 50%

As expected, total inleakage will be determined with little uncertainty. Inleakage from specific tagged locations will be determined with about ±15 to 20% uncertainty and that from remaining untagged locations plus directly from outdoors will be combined to a single remaining inleakage with an uncertainty from ±20 to 50% of the flow rate. As a percentage of total inleakage, all individually determined zonal inleakages will have uncertainties less than ±10%.

The above table just reflects how well the results will be quantified, regardless of individual magnitudes. It does not matter whether almost all the inleakage is via the Aux. Bldg. and little from elsewhere, or if almost all is directly from outside or other untagged areas of the plant. If the latter is the case, then subsequent tests should be conducted in which untagged areas are now tagged; an evolution of refined testing will ultimately identify the more significant pathways which should enable effective mitigating strategies.

Extended Multizone Testing

Moving beyond the 3 primary zones – CR, Aux. Bldg., and Turbine Bldg., is important primarily for mitigation strategies, if needed. If the 3-zone results show that the CR total inleakage is sufficiently contained, then extending the testing to the tagging of subzones is not needed. Only if the primary zones testing indicates undesirable inleakage would it be necessary to consider tagging of suspect leakage locations in order to identify and quantify the more problematic areas.

Appendix B describes an estimation of anticipated results from the pilot facility example, in which extended multizone testing includes:

a. Subdividing the Aux. Bldg. from its two Component Cooling Pump rooms (Zone 4 – which comprises 20% of the Aux. Bldg.'s fan SA use) by tagging with a separate tracer;
b. Separately tagging the 45′ vestibule area (Zone 5);
c. Separately tagging the 27′ vestibule area (Zone 6); and
d. Now tagging the previously untagged Switch Gear Rooms (SWGRs) on each of 2 levels (Zone 7).

The primary 3-zone testing results of 3000 cfm inleakage was considered excessive for the purpose of continuing to the extended mutizone test. The above most likely areas were also "tagged" (mathematically) and the "results" computed in Appendix B. The CCPRs were chosen because the inleakage from the Aux. Bldg. was relatively large (and this was a known leakage pathway); the SWGRs were chosen because outside air) could communicate with the CR via this subsystem.

Summary Initial Protocol

The simplest inleakage test to perform at any power plant would be a 1-zone test with tagging at the CR's recirculation fan – similar to the simple way in which SF_6 tracer decay tests are performed. This requires the least investment in understanding the air handling systems of the plant other than that for the Control Room. This method provides an accurate measurement of inleakage but is limited in that it does not identify leakage pathways.

The next level of test complexity would be to tag the plant's primary zones – such as the Control Room, Aux. Bldg., and Turbine Bldg. at their respective SA locations. The Appendix A results show that the total inleakage is still precisely determined, but now there is a further indication of where the inleakage is occurring. In the Appendix A simulation, the Aux. Bldg. dominates the source of inleakage followed by that from an untagged location.

As a result of the 3-zone testing, further study of the plants HVAC systems is needed in order to effectively tag and sample other highly suspect locations. This requires a larger investment in up front study and planning, but the result will be confirmation (or denial) of the major suspected inleakage pathways *without* any compromise in verification of the CR total inleakage, both magnitude and uncertainty. The latter is demonstrated in that the Appendix B results give the same CR total inleakage and uncertainty as that calculated in the Appendix A 3-zone results.

Plant engineers will need to work with Brookhaven staff to choose the initial approach – 1-zone (simple); 3-zone (more moderate effort); or a many multizone (detailed and more complex) testing. The former is the least costly and possibly the most cost-effective approach if inleakage is suspected of being acceptable. The latter is the most costly but still a most cost-effective approach if inleakage is highly suspected of being excessive; the excessive inleakage will be confirmed and suspect areas for the location of the excess inleakage will be documented. Another benefit of the many multizone testing will be that the tagging and sampling locations will have been evaluated for their effectiveness. A much smaller number of samplers will be needed for subsequent testing at substantial cost savings.

Repeat Testing, Periodic Testing, and/or Continual Integrated Recording

Following the initial testing approach, regardless of which is chosen, Repeat Testing may be conducted to document the locations of the major inleakage pathways in order to effect mitigation. The effectiveness of any mitigating strategies can then be confirmed with additional repeat testing. Once the PFT sources have been set in place and the representative sampling locations have been assigned, repeat testing can be cost-effectively performed with plant personnel alone; samplers need only be returned to BNL for analyses and the generation of a report. Repeat testing would be concluded when the CR inleakage was mitigated to an acceptable level.

Using the same assigned tagging and sampling locations, Periodic Testing could be done every so often to confirm acceptable inleakage. Alternatively, or possibly in addition, Continual Integrated Recording could be employed. Samplers could be left in place continually, being changed, say, on a monthly basis. Unless there was a reason to analyze the results, the samplers would be recycled for a minimal charge. However, if there was an incident for which confirmatory knowledge of the inleakage was highly desirable, the samplers could be immediately exchanged, analyzed, and a report generated.

Other variations of continual testing/recording of inleakage could be devised.

Conclusions

The PFT technology can be adequately applied at this stage, in groups of 7-zone testings to quantify the magnitude and uncertainties of air inleakage and outleakage involving the Control Room and other plant locations. The technology will identify problematic areas and suggest the likely causative pathways for confirmation by subsequent testing. Future routine or continuing inleakage testing is feasible. Details of simulated results for 3-zone and 7-zone testing acknowledge the technology's potential.

References

1. Dietz, R.N. Perfluorocarbon tracer technology. In Regional and Long-Range Transport of Air Pollution, Sandroni, S., pp. 215-247, Elsevier Science publishers B.V., Amsterdam, the Netherlands, 1987. (Note: this key paper is available on our web site: http://www.ecd.bnl.gov/TTC.html
2. Dietz, R.N., Goodrich, R.W., Cote, E.A., and Wieser, R.F. Detailed description and performance of a passive perfluorocarbon tracer system for building ventilation and air exchange measurements. In Measured Air Leakage of Buildings, ASTM STP 904, H.R. Trechsel and P.L. Lagus, Eds., pp. 203-264, American Society for Testing and Materials, Philadelphia, 1986.
3. D'Ottavio, T.W., Senum, G.I., and Dietz, R.N. Error analysis techniques for perfluorocarbon tracer derived multizone ventilation rates. Building and Environ. 23 (3), 187-194 (1988).
4. Dietz, R. Safe Use of Perfluorocarbon Tracers (PFTs). BNL Memorandum, Nov. 24, 1992 (attached).
5. Senum, G.I. and Dietz, R.N. The Global Warming Impact of Perfluorocarbon Tracers. BNL Brief Note. Oct. 13, 1998 (attached).

APPENDIX A: Air Inleakage Calculations – Expected Primary Results

As shown in Figure 1, the 3 tracer types, deployed uniquely in the 3 zones, plus the CATS, to measure the best steady state average tracer concentration for all 3 PFTs in each of the 3 zones (9 concentrations), can be used to quantitatively determine all the flows shown and their uncertainties. The matrix solutions for flow rates:

$$\mathbf{C} * \mathbf{R} = \mathbf{S} \qquad (1)$$

or

$$\mathbf{R} = \mathbf{C}^{-1} * \mathbf{S} \qquad (2)$$

and uncertainties:

$$\boldsymbol{\Delta}\mathbf{R} = [(\mathbf{C}^{-1})^2 \, (\boldsymbol{\Delta}\mathbf{S}^2 + \boldsymbol{\Delta}\mathbf{C}^2 \, \mathbf{R}^2)]^{1/2} \qquad (3)$$

have been presented(3).

In order to get an advance look at expected results for the 3-zone computation (Z1: CR; Z2: Auxiliary Building; Z3: Turbine Building), the 3000 cfm air inleakage previously determined with the single tracer, SF_6 and an elementary knowledge of the physical conditions affecting ventilation at the pilot facility were used to estimate the flowrates (cfm) shown in Table A. These flows plus the planned source rates were used to calculate the expected tracer concentration matrix (ppt) from re-arranging Equation 1:

$$\mathbf{C} = \mathbf{S} * \mathbf{R}^{-1} \qquad (4)$$

The resulting calculated expected concentration matrix results are shown in Table A. Also listed for the 3-zones are the PFT source rates that will be used.

Then, given the source rate matrix (**S**), the concentration matrix (**C**), and the expected uncertainties for each, Equation 2 was used to calculate all the flow rates and Equation 3, all the anticipated flow rate uncertainties. The recalculated flow and uncertainty results are shown in parentheses in Table A. Note that the source rate uncertainty was ±5% in the CR and Auxiliary Building and ±10% in the Turbine Building. Also, the expected concentration variabilities over all locations in each zone ranged from the tightest (±5%) in the CR to the broadest (±15%) in the Turbine Building.

In the top section of Table A are listed the exfiltration and infiltration flows for each of the 3 zones. Infiltration is flow from outside air (or any untagged zone) into the particular zone and exfiltration is flow from the zone directly to the outside air (or, again, any untagged zone). Note that for the Aux. Bldg. and Turbine Bldgs., the infiltration rates should be comparable to the sum of the rated SA fan capacities. For the Aux. Bldg., this flow is expected to be calculated with an uncertainty of ±10 to 15%. For the Turbine Bldg., the uncertainty will be larger, primarily because of an expected wider variation of the tracer concentration in that zone as well as a larger uncertainty in the source strength due to greater uncertainty in the fan location temperatures. Note also that the “calculated” Turbine Bldg flowrate exceeds the 12-fan rating of about 600,000 cfm due to an assumed stack effect from the usual open doors.

The next section gives the Zone To Zone Air Exchange rates and their calculated uncertainties. Each line provides the flowrate from one zone into another zone and its reverse. For example, the first line is the flow from Zone 1 into Zone 2 followed by that for Zone 2 back into Zone 1, etc. Note that for flows into a zone with a small source rate uncertainty as well as concentration variability, the calculated percentage flow rate uncertainty is much smaller than for flows into a zone with larger uncertainties in source rates and concentrations. For example, uncertainties into Zone 1 are a respectable ±13 to 18%, whereas into Zone 3, a larger ±25%. Fortunately, in Control Rooms (Zone 1), the recirculation rate are always quite high, assuring that concentration variabilities within that zone will be small – likely much less than ±5%. Further, the individually calibrated, typically single source, deployed in a well-known temperature environment will assure that the source rate uncertainty will also likely be ±5% or less. Thus, CR inleakage will be determined with small uncertainties.

The third section provides the total zonal flow rates and uncertainties. Referring to Fig. 1, mathematically, the total zonal flow for the Control Rm, Zone 1 (R_{11}), is:

$$R_{11} = R_{01} + R_{21} + R_{31} \tag{5}$$

$$= R_{10} + R_{12} + R_{13} \tag{6}$$

Thus, Eq. 5 represents the total of all inflows or *total inleakage*. Of course, from a material balance viewpoint, it is also equal to the total of all outflows (Eq. 6). Mathematically, however, the uncertainty for the total inleakage is **not** computed via Eq. 5 **nor** from the uncertainties of the flow rates in Eq. 5, but rather from the full matrix Eq. 3. Thus, the total zonal inleakage always has the smallest **percentage** uncertainty of any of the flows associated with that zone.

The fourth section lists the tracer types, quantity, and rates used in each zone, the calculated average tracer concentration of each of the 3 PFTs in each of the 3 zones, and, in this case, the estimated assigned uncertainties for the source rates and concentrations. In an actual field test, the tracer concentration uncertainties will be set equal to the standard deviation of the average of each from multiple sampler results in the same zone. Thus, one typically would not want to use less than 2 to 4 samplers per zone, depending on the complexity of the zone.

Finally, the last section summaries the 4 inleakage flow rates (Eq. 5). Notice that indeed the percentage uncertainties is the smallest for the total inleakage. The largest contributor to total inleakage was from the Aux. Bldg.; 1580 cfm represents 53% of the total. Thus, a suspect subzone or two of the Aux. Bldg. should be separately tagged to further refine the location for potential mitigation strategies. The next largest inleakage contribution was from outside air (or any untagged zone). The Switch Gear Rooms (SWGRs) have been suspect candidate locations for additional tagging. This extended zone testing is demonstrated in Appendix B.

Table A. Estimated Flows (cfm), Calculated Concentrations, and Recalculated Flows and Uncertainties

Zone	**ID**		**Exfiltration (Calc ± Error)**			**Inleakage (Calc ± Error)**	
1	CR	R_{10}:	500	(494 ± 358)	R_{01}:	825	(826 ± 203)
2	AB	R_{20}:	96,970	(97,100 ± 11,200)	R_{02}:	100,045	(100,200 ±11,300)
3	TB	R_{30}:	703,730	(703,000 ±127,000)	R_{03}:	700,330	(700,000 ±126,000)

	Air Exchange (Calc ± Error)				
R_{12}:	1,500	(1,510 ± 240)	R_{21}:	1,575	(1,580 ±210)
R_{13}:	1,000	(1,002 ± 251)	R_{31}:	600	(601 ±105)
R_{23}:	6,000	(6,000 ±1,580)	R_{32}	3,000	(3,000 ±655)

Zone	**ID**		**Total Zonal Flows (Calc ± Error)**	
1	CR	R_{11}:	3,000	(3,003 ± 213)
2	AB	R_{22}:	104,545	(104,700 ± 11,800)
3	TB	R_{33}:	707,330	(707,000 ±127,000)

		PFT Sources				**Calc. Conc., ppt**		
Zone	**ID**	**Type**	**Qty**	**Rate, µL/h**		**PFT1 (± 5%)**	**PFT2 (±10%)**	**PFT3 (±15%)**
1	CR	ptPDCH	1	48	(±5%)	9.486	2.154	0.416
2	AB	PMCP	4	720	(±5%)	0.1366	4.085	0.0610
3	TB	PDCE	12	2,304	(±10%)	0.0146	0.0377	1.918

<u>Summary of Control Room Inleakages:</u>

Item	**Rate**	**Flow (cfm) ± Error (±%)**
Total Inleakage	R_{11}	3,003 ± 213 (±7.1%)
Outside/Inleakage[*1]	R_{01}	826 ± 203 (±25%)
From Auxiliary Building	R_{21}	1,580 ± 210 (±13%)
From Turbine Building	R_{31}	601 ± 105 (±17%)

[*1] Includes inleakage from other non-tagged locations as well.

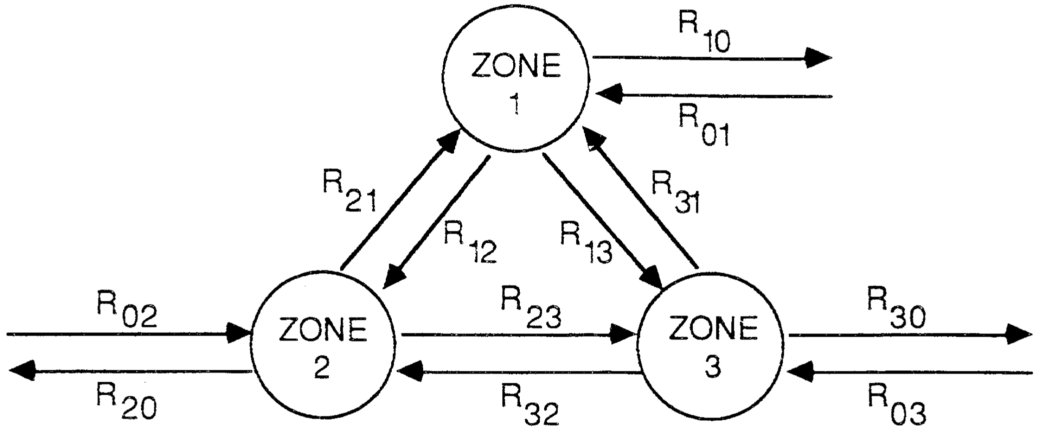

Fig. 1. Air flow schematic for a building that consists of three well-mixed zones. Zone 0 is outdoors.

APPENDIX B: Air Inleakage Calculations – Extended 7-Zone Results

A further advance look at expected results and their interpretation regarding locations and mitigation strategies for reducing Control Room inleakage is presented in Tables B1 to B3 for the 3 primary zones and an additional 4 secondary zones. From Table B1 it is immediately seen that a lot of flow information is generated because for *N* zones, the number of flowrates computed is equal to N^2. The procedure used was similar to that for the Appendix A 3-zone case, but more effort was applied to attempting to estimate the larger number of exchange flow rates.

First, in Table B1, note that the total zonal flowrates for the first 3 zones are essentially the same as in the 3-zone case (Table A); adding more zones did not diminish the effectiveness of their determinations. The exfiltration from Zone 2 (Aux. Bldg.) is now lower by 16,000 cfm because the CCPRs were separately tagged; they have an exfiltration rate of 16,190 cfm (Zone 4). Similarly, but more importantly, the infiltration into Zone 1 (Control Rm) directly from outside air (or remaining untagged zones) is down by about 500 cfm because it now shows up as 512 cfm from the SWGRs (Zone 7 into Zone 1).

The entire Aux. Bldg. Zone 2 was tagged with the Zone-2 tracer, PMCP, including the CCPRs (Zone 4). But that zone was also separately tagged with the Zone-4 tracer, PMCH (Table B2). Thus, although there is a total flow of 20,000 cfm through this zone as designed (Zone 4 total zonal flow of 20,210 cfm), it is primarily interpreted as a zone-zone air exchange (Zone 2 – Zone 4 of 18,940 cfm). Similarly, the SA vent in the 45′ vestibule from the Control Rm HVAC (design set to 246 cfm), shows up as a Control Rm to vestibule zone-to-zone flow (Zone 1 – Zone 5 of 256 cfm).

A summary of the total Control Rm inleakage as well as that from outside and the 6 other zones plus the outleakage flows as well are shown in Table B3. The total inleakage and uncertainty is still as it was for the 3-zone case (as it should). Now the largest inleakage is from the CCPRs; the lack of any significant flow back to the CCPRs implies the cause would be a pressure imbalance. Similarly, the SWGRs provides a large inleakage without any significant reverse flow (512 vs 26 cfm); again, a pressure differential would be the cause. Mitigation in these 2 cases would suggest attempts to minimize those pressure differences – rather than trying to seal the pathways.

As devised for this example, the two vestibules do not account for a significant outleakage from the Control Room. The exfiltration from the 27′ vestibule may be via the 2 Unit-1 Battery Rooms, directly to outside. The largest CR outleakage is via the Aux. Bldg.

In conclusion, the flow information presented here was all devised, but, hopefully, reflects, to some extent, the actual physical picture as it exists at the plant. The purpose was not only to demonstrate the type of information that will be obtained from “real” tracer tests, but also to be certain that the approach was technically and mathematically sound. Both of the latter seem to be true. Note again that the uncertainties in all 7 of the individual inleakages (Table B3) were numerically smaller than the uncertainty of the total inleakage.

It is also clear, however, that there are many more secondary areas that would need to be individually tagged in separate 7-zone tests. As real tests are completed, analyzed, and the results studied, this will provide direction for subsequent tests.

Table B.1 7-Zone Recalculated Flowrates (cfm) and Uncertainties

Zone	ID	Exfiltation	Infiltration	Total Zonal Flow
1	CR	500± 290	311± 174	3,002± 214
2	AB (-CCPRs)	80,400± 10,200	100,000± 11,400	104,500± 11,900
3	TB	705,000±127,000	700,000±126,000	708,100±127,700
4	CCPRs	16,190± 2,650	739± 2,620	20,210± 2,890
5	45′ Vest.	14± 55	3± 14	268± 25
6	27′ Vest.	325± 71	286± 32	586± 55
7	SWGRs	11,310± 1,330	2,401± 340	2,533± 359

Zone-Zone	Air Exchange	Zone-Zone	Air Exchange
1-2	1,320 ± 214	2-1	437 ± 187
1-3	588 ± 193	3-1	601 ± 105
1-4	89 ± 56	4-1	1,121 ± 151
1-5	256 ± 35	5-1	15 ± 2
1-6	224 ± 31	6-1	6 ± 1
1-7	26 ± 5	7-1	512 ± 68
2-3	4,690 ± 1,420	3-2	1,554 ± 351
2-4	18,940 ± 3,850	4-2	1,527 ± 318
2-5	-0 ± 16	5-2	0 ± 1
2-6	-0 ± 20	6-2	0 ± 1
2-7	41 ± 9	7-2	94 ± 46
3-4	441 ± 133	4-3	1,318 ± 390
3-5	6 ± 8	5-3	221 ± 56
3-6	12 ± 8	6-3	252 ± 63
3-7	65 ± 15	7-3	616 ± 176
4-5	0 ± 13	5-4	-0 ± 0
4-6	47 ± 16	6-4	0 ± 0
4-7	0 ± 2	7-4	-0 ± 12
5-6	18 ± 3	6-5	3 ± 1
5-7	-0 ± 0	7-5	0 ± 9
6-7	9 ± 0	7-6	0 ± 5

Table B2. Summary Tagging Rates and Concentration Uncertainties

		PFT Source				Assumed
Zone	ID	PFT	Type	Qty.	Rate, µL/h (±%)	Conc. ±%
1	CR	ptPDCH	Mega	1	48 (5)	5
2	AB (-CCPRs)	PMCP	Mega	4	720 (5)	10
3	TB	PDCB	Mega	12	2,304 (10)	15
4	CCPRs	PMCH	Low Mega	4	106 (10)	10
5	45′ Vest.	ocPDCH	Reg.	4	1.53 (5)	8
6	27′ Vest.	PTCH	Reg.	8	2.25 (5)	8
7	SWGRs	iPPCH	Reg.	14	7.90 (10)	10

Table B3. Summary of Control Room Inleakage and Outleakage (cfm)

Total Inleakage (Outleakage): 3,002 ± 214 cfm

From / To	CR Inleakage			CR Outleakage		
Outside	311	±	174	500	±	294
AB (-CCPRs)	437	±	187	1,320	±	214
TB	601	±	105	588	±	193
CCPRs	1,121	±	151	89	±	56
45′ Vest.	15	±	2	256	±	35
27′ Vest.	6	±	1	224	±	31
SWGRs	512	±	68	26	±	5