BNL-61990
Informal Report

MEASUREMENT OF HVAC SYSTEM PERFORMANCE AND LOCAL VENTILATION USING PASSIVE PERFLUOROCARBON TRACER TECHNOLOGY

Russell N. Dietz and Robert W. Goodrich
Environmental Chemistry Division
Department of Applied Science
Brookhaven National Laboratory
Upton, NY 11973-5000

June 1995

Prepared in part for the
State University of New York,
College of Technology
Farmingdale, NY

UNDER CONTRACT NO. DE-AC02-76CH00016 WITH THE
UNITED STATES DEPARTMENT OF ENERGY.

ABSTRACT

Two several-day integrated ventilation tests using passive perfluorocarbon tracer (PFT) technology were performed on a 4-story college campus building operated with 5 air handling (AH) systems in the core and individual units in the perimeter. The HVAC system performance for this demonstration was confined to the 4 core AHs that were operating -- AC2 and 3, which handled the west and east halves, respectively, of floors 2, 3, and 4, and AC4 and 5, which each handled individual lecture halls on the second floor. Local ventilation was assessed in 13 rooms during the second test by deployment of a PFT source in each room as a surrogate pollutant source for local emissions such as CO_2 from the breath of occupants.

The infiltration, exfiltration, and air exchange rates measured for the 4 AH systems were identical within the standard deviations of the results for the two tests. Fresh air ACH (air change per hour) rates for the four zones were 2.6, 1.7, 2.1, and 6.9 h^{-1}, respectively. Based on assumed occupancy levels during daytime use, it was estimated that the four ACH rates should have been 2.6, 2.7, 9.0, and 9.5 h^{-1}, respectively, to maintain each of the entire zones CO_2 levels at about 520 ppm. A literature review of other building tests indicated that at greater than 600 ppm CO_2 there was a reduction in satisfaction with perceived indoor air quality (IAQ). Reducing outside air ACH to 0.5 h^{-1} during nights and weekends plus comfort temperature setbacks during these periods would reduce energy consumption for heating by about 30%.

Two of the 13 rooms tested with the "surrogate" PFT source were the lecture rooms controlled entirely by separate AHs, thus, there was no local ventilation issue in those. Four of the remaining 11 rooms on the other two AH systems had poor predicted local ventilation for the occupancy levels assigned; predicted CO_2 levels for those four ranged from 902 to 1003 ppm. Remediation would have required increasing the number of SA grills by 1 or 2 and increasing the local fresh air rate by 2- to 3-fold as well.

The PFT technology can provide an independent quantifiable assessment of the interactive performance of multiple AH units and of the local ventilation magnitude in each room served by the same AH. The technology can be used for commissioning certification of new building AH performance and as a diagnostic tool in sick building syndrome investigations.

INTRODUCTION

In April of 1993, two (2) perfluorocarbon tracer (PFT) ventilation/indoor air quality assessment tests were performed in the Gleeson Hall building of the SUNY Farmingdale campus. The building was being modified, in part, as a result of significant occupant complaints of perceived poor air quality. Arrangements were made by Integrated Innovation Inc., in cooperation with SUNY Farmingdale, to invite Brookhaven to demonstrate the feasibility and utility of their passive BNL/AIMS (air infiltration measurement system) technique with a subsequent goal of determining if the SUNY education system wished to include the technology in the syllabus of their HVAC education program.

The four story (22,000 ft^2/floor) building had a basement first floor with air supplied normally by an HVAC system labelled as AC1. During this study, AC1 was inoperational and the basement interior rooms (walls) were primarily gone; the other three floors were still being used for classes. It is possible that a sense of poor air quality may have been perceived by first-floor occupants because they were working in the basement, but this issue could not be addressed.

The second floor (at ground level with 200-series room numbers) had two (2) lecture halls -- Rm 202 (handled by AC4) and Rm 204 (handled by AC5); the balance of the second floor interior rooms and corridors was split between two other air handling systems, AC2 for the west side of the building and AC3 for the east side (cf., Fig. 1). The remaining 3rd and 4th floors (cf., Figs. 2 and 3) were also split about evenly between AC2 and AC3. The perimeter rooms, equipped with wall units having their own outside air (OA) source plus centralized return air (RA) bypasses, were not included in this testing which was restricted to the basement floor (1st floor) and the four operating air handling systems, AC2 to AC5, during Test 1 and only AC2 to AC5 during Test 2.

Two types of tests were performed using the full suite of 5 PFT types available. The first test was designed to measure the infiltration, exfiltration, and air exchange between the 5 AC zones above and the second test used the 5th tracer, which had been in the basement, as a distributed source throughout the four other zones to act as a surrogate pollutant source -- such as CO_2 from the breath of office personnel, teachers, and students.

This report provides final conclusions of both tests and suggestions regarding its usefulness in similar building ventilation and indoor air quality assessments.

EXPERIMENTAL

Details on the use of the BNL/AIMS technology[1] and the calculation of ventilation rates and their uncertainties[2] have been presented elsewhere. The number of PFT sources used in each zone (cf., Table 1) were tailored to expected ventilation rates and zone volumes in order to achieve primary tracer zonal concentrations of about 0.5 to 1.0 parts-per-trillion (ppt) which is equivalent to picoliters per liter (pL/L) or nanoliters per cubic meter (nL/m^3).

Table 1
Number of PFT Sources and CATS Samplers Used

Test		Zones			PFT Sources		Sampler Qty In:		
No.	Period	No.	Location	Vol., m^3	Qty	Type	Room	Corr.	SA Grills
1	4/7-9/93	1	1st Floor	8200	14	oPDCH	5	--	--
		2	AC2	4580	3	PMCP	6	4	--
		3	AC3	5100	5	PMCH	8	1	--
		4	AC4	740	3	pPDCH	3	--	--
		5	AC5	680	6	PTCH	3	--	--
2	4/9-12/93	1	AC2	4580	3	PMCP	6	4	3
		2	AC3	5100	5	PMCH	8	1	3
		3	AC4	740	3	pPDCH	3	--	2
		4	Rm 204	680	6	PTCH	3	--	2
		All	(Pollutant surrogate)		14	oPDCH	--	--	--

Test 1 was performed as a 5-zone study to assess the general ventilation performance of the building in its then current state prior to reconstruction of the layout of rooms and ventilation controls. The number of sources and samplers deployed is shown in Table 1. The first floor air handler (AH), AC1, was not operating because of the reconstruction, so the 14 PFT sources were distributed uniformly around that level; it would be expected that that floor's ACH (air change per hour) rate should be low both because the AH was not operating and the first floor was below grade (few air leakage locations).

The next three (3) zones, AC2 to AC4, were tagged by deploying the PFTs within a nylon stocking which was suspended in the appropriate return air (RA) duct locations, that is, after any exhaust air (EA) location but before the addition of any outside air (OA) so that source temperature would be accurately known. The last zone, Lecture Rm 204, handled by AC5, had the 6 PFT sources distributed uniformly throughout the room because initially (on 4/7/93) the AH was not running; it was operating on 4/9/93 when the Test 1 sampling was terminated. It was also operating throughout Test 2, but the sources were left in their original locations.

During Test 1, samplers were deployed throughout numerous rooms of the five zones and also in the corridors of the 2nd, 3rd, and 4th floors. During Test 2, samplers were also deployed in the supply air (SA) grill in order the distinguish mechanical OA from natural infiltration directly into each of the four zones. However, mechanical outside air from the perimeter rooms would appear as natural infiltration in the tested zones, so this calculation was not performed.

RESULTS

Ventilation Calculations

The complete BNL-AIMS output sheets for the two tests are shown in the Appendix as Table A1 and A2. A general discussion of the output format shows, at the top of the sheet, the sampling period, the date the samplers were analyzed, and the date the results were computed. The next section, "Rates", gives the overall ACH for all zones tested followed by the individual zone results, starting on the left with zone number and name, the PFT source rate (nominal and corrected for number used and zone temperature), the exfiltration rate and standard deviation (SD), and the infiltration rate and SD (both in m^3/h and in h-1, that is, rate divided by zone volume).

Next are the zone-to-zone air exchange rates and their SDs. For example, 1-2 means the air flow from zone 1 (1st floor in Test 1) to zone 2 (AC2) was 805 ± 176 m^3/h; flow in the reverse direction (2-1) was 837 ± 171 m^3/h or about equal air exchange in both directions. Zones which had little air exchange were AC4 to AC5 (4-5 in Test 1) and reverse (<100 m^3/h);those with large air exchange were AC2 to AC3 (2-3 in Test 1) and reverse at 3,000 to 4,000 m^3/h--quite natural since these AHs conditioned space that was open to shared corridors on each of these floors. Lastly, are the Total Flow In or Out rates which is the sum of all flows from outside air and from all other zones or to outside and to all other zones.

The next section, "Analysis", gives, in the upper part for each zone, its volume and the PFT source type deployed followed by the average PFT concentration and SD for the primary zone tracers found in each zone. Note that the highest PFT concentration should occur in the zone in which that PFT was deployed, that is, the diagonal locations in the average tracer concentration matrix. On the second page are the concentrations of each PFT found on each CATS sampler tube. When the word "DELETED" appears, it means those values were not included in the averages above. For example, location M7 on the first floor, corridors C46 and C48 on the 4th floor, etc., were deemed not to be representative of the concentrations found elsewhere in those zones and were excluded from the averages. In Test 2 (Table A2), samplers deployed in SA grills were also deleted.

The last section, "Notes", contains among other items, the overall normalized concentration matrix condition number (0.502 in Test 1; 0.543 in Test 2) and the zonal condition number (near unity). When the former is less than 2, the test is quite good; these tests were exceptional. It should be noted that the rates shown in the upper section are computed from the source rates and average tracer concentrations as follows using matrix notation:

$$\mathbf{R} = \mathbf{C}^{-1}\mathbf{S} \tag{1}$$

This solution and the matrix solution for the standard deviations have been presented elsewhere.[2]

Indoor Air Quality (IAQ) Assessment

As described above, the PFT technology can completely characterize the air flows in a multizone building. But the same technology, when an additional PFT is used as a surrogate pollutant source throughout various rooms of the same building, can be used to calculate an apparent local ACH and local air quality.

For this school building. the major air quality issue would be local CO_2 levels generated from the breathing of students, teachers, and administrative personnel as non-uniformly distributed CO_2 sources. A sedentary adult will emit about 19 L/h of CO_2, an active adult 24 L/h, and active child 14 L/h. For the evaluation here, the sedentary adult rate (19,000 mL/h) was used. As indicated in Table 1, 14 oPDCH sources were deployed in various rooms in all four zones of Test 2, one in each of 12 rooms and 2 in the 13th -- Room 204, served by AC5.

In each of these rooms, there is a local rate of ventilation based on air exchange between the room and both supply air (SA) and adjacent room(s) which is equal to the vapor source strength in the room divided by the change in concentration of the vapor in the room due to that source, namely,

$$R_\ell = \frac{S_\ell}{\Delta C_\ell}$$

where the local vapor can be from either the oPDCH PFT source deployed in the room or the expected CO_2 source (the number of people in that room times the adult CO_2 generation rate).

The relationship between the change in concentration of ocPDCH (the measured isomer of the deployed oPDCH source) and its local source strength and that between the change in the local pollutant concentration (e.g., CO_2) and its local source strength (the number of people in the room times S_{CO_2}) is a function of the time required to ventilate a local area or, in terms of the local ventilation rate above,

$$R_\ell = \frac{S_\ell^{oc}}{C_R^{oc} - \overline{\Delta C_z^{oc}}} = \frac{nS_{CO_2}}{C_R^{CO_2} - 360 - \overline{\Delta C_z^{CO_2}}} \qquad (2)$$

where R_ℓ is the local ventilation rate (m^3/h); S_ℓ^{oc} is the local ocPDCH surrogate pollutant emission rate (nL/h); nS_{CO_2} is the adult CO_2 emission rate (n x 19,000 mL/h) for "n" people present; C_R and $\overline{\Delta C_z}$ are the respective local room and incremental zonal average concentrations (nL/m^3 for ocPDCH and mL/m^3, i.e., ppm, for CO_2); and 360 is the ambient CO_2 concentration (ppm). The right denominator in Eq. 2 is the incremental or change in local room CO_2 concentration, that is

$$\Delta C_{\ell}^{CO_2} = C_R^{CO_2} - 360 - \overline{\Delta C}_z^{CO_2} = \frac{nS_{CO_2}}{S_{oc}}\left(C_R^{oc} - \overline{\Delta C}_z^{oc}\right) \quad (3)$$

The left side of Eq. 2 can be used to compute the local ventilation rate in rooms tagged with the oPDCH source (S_{oc} is known and C_R^{oc} is locally measured) if the zonal average ocPDCH concentration, $\overline{\Delta C}_z^{oc}$, can be determined. Table 2 provides the data used to calculate the room ocPDCH concentration which would have been present from zonal SA only assuming that the ratio of Grill/Room concentrations for the PFT used in the zone would have the same ratio for other PFTs (including the pollutant surrogate) supplied via the grill. Note that PMCH was used for zone 4 (AC5, Room 204) because the PTCH used in that zone was deployed in the room rather than via the SA ducting. The last column, predicted ocPDCH change in concentration, will be described shortly.

Table 2
Estimated Zonal Surrogate Pollutant (ocPDCH) Concentration

			Zone PFT Conc., nL/m^3		"Surrogate" $\overline{\Delta C}_z^{oc}$ ocPDCH Conc. Change, nL/m^3		
Zone	AH	PFT	Grill	Room	Grill	Room	Predicted
1	AC2	PMCP	0.51 ± 0.02	0.37 ± 0.01	0.18 ± 0.03	0.13 ± 0.02	0.174
2	AC3	PMCH	0.56 ± 0.02	0.56 ± 0.02	0.22 ± 0.02	0.22 ± 0.02	0.222
3	AC4	ptPDCH	0.74 ± 0.02	0.65 ± 0.02	0.23 ± 0.00	0.20 ± 0.01	0.217
4	AC5	PMCH	0.050 ± 0.001	0.044 ± 0.001	0.10 ± 0.01	0.09 ± 0.01	0.155

The right side of Eq. 3 can be used to compute the expected change in room CO_2 concentration if the zonal CO_2 concentration change is known; the latter is the average expected change in CO_2 concentration in each AH zone based on the assumption that the CO_2 emitted from all the people in that zone was released at the same location in the RA duct where the zonal PFT sources were deployed. The PFT concentration matrix from Table A2 in the Appendix is repeated in Table 3 below along with the respective PFT source rates. An estimate of the number of people present in each of the various rooms comprising the entire zones is also given in Table 3, from which the estimated total CO_2 source strength per zone is given. Then, for each zonal column, the incremental ΔCO_2 concentration, that is, concentration above ambient for the entire zone, is calculated by

Table 3
Estimated Zonal Incremental CO_2 Concentrations

Zone	AH	S_{PFT}, nL/h	C_{PFT}, nL/m^3 1	2	3	4	Est. No. of People (n)	nS_{CO_2} [1] 10^6mL/h	ΔC_{CO_2}, mL/m^3 1	2	3	4	$\overline{\Delta C}_z^{CO_2}$
1	AC2	5773	0.372	0.135	0.033	0.002	77	1.46	94	46	27	1	168
2	AC3	6667	0.089	0.559	0.028	0.012	120	2.28	23	191	23	9	246
3	AC4	1389	0.075	0.063	0.653	0.004	60	1.14	19	22	536	3	580
4	AC5	1541	0.028	0.049	0.014	0.285	60	1.14	7	17	11	211	246

[1] S_{CO_2} = 19,000 mL/h • person

$$\Delta C_{CO_2} = C_{PFT} \frac{nS_{CO_2}}{S_{PFT}} \tag{4}$$

and summing over all four CO_2 sources strengths gives the total zonal incremental or change in CO_2 concentration in the last column of Table 3.

This same procedure can be used to estimate or predict the zonal ocPDCH concentration. Using the same PFT concentration and source matrices from Table 3, Eq. 4 (but for ocPDCH) was used to calculate the predicted incremental zonal ocPDCH concentration as shown in Table 3a below and also listed in Table 2. It can be seen in that table that the predicted values agree very closely with the values measured in the SA grills for all but AC5. Because there were so few measured values, the predicted zonal ocPDCH incremental concentrations were the ones used in Table 4 along with other pertinent room information. Substitution into Eqs. 2 and 3 gave the room's local ventilation rate, R_ℓ (m^3/h), apparent ACH (h^{-1}), and the local incremental and

Table 3a
Predicted "Surrogate" Pollutant (ocPDCH) Concentration

Zone	No. of ocPDCH Sources (n)	n S_{oc}, nL/h	"Surrogate" ocPDCH Conc., nL/m^3 (ΔC_{oc}) 1	2	3	4	Predicted
1	5	1856	0.120	0.044	0.009	0.001	0.174
2	6	2157	0.029	0.181	0.007	0.005	0.222
3	1	363.4	0.024	0.020	0.171	0.002	0.217
4	2	680.7	0.009	0.016	0.004	0.126	0.155

Table 4
Estimated Local Ventilation and Room CO_2 Concentrations

AH	Room No.	Vol., m^3	No. of SA Grills	S_{oc}, nL/h	C_R^{oc} nL/m^3	$\overline{\Delta C}_z^{oc}$ nL/m^3	R_ℓ m^3/h	App. ACH, h^{-1}	No. of People (n)	nS_{CO_2}, 10^3 mL/h	Predicted CO_2 Conc., ppm: $\overline{\Delta C}_z$	ΔC_{local}	$\Delta C_{R/person}$[1]	C_R	R_ℓ/Grill, m^3/h
AC2	444A	50	1	371	1.257	0.174	343	6.9	1	19	168	55	57	583	340
"	341	124	1	371	0.614	0.174	844	6.8	2	38	168	45	25	573	840
"	342	272	2	371	0.608	0.174	855	3.1	8	152	168	178	24	706	430
"	208A	376	9	371	0.182	0.174	>40,000	>100	20	380	168	8	2.6	536	--
"	208C	268	8	371	0.200	0.174	14,300	53	18	342	168	24	3.5	552	1,800
AC3	419	217	3	360	0.395	0.222	2,078	9.6	7	133	246	64	11.2	670	690
"	421	258	2	360	0.375	0.222	2,350	9.1	8	152	246	65	10.2	671	1,200
"	323	158	4	360	0.546	0.222	1,110	7.0	20	380	246	342	19	948	280
"	339	382	3	360	0.653	0.222	834	2.2	15	285	246	342	25	948	280
"	209B	118	2	360	1.146	0.222	389	3.3	2	38	246	98	51	704	190
"	213	76	2	360	0.782	0.222	642	8.4	10	190	246	296	32	902	320
AC4	202	740	6+	363	0.237	0.217	18,170	24	60	1,140	580	63	10.7	1,003	3,000
AC5	204	680	6+	681	0.17-0.23	0.155	9,000-45,000	13-66	60	1,140	246	25-125	4.5-6.2	630-730	1,500-7,500

[1] From Eq. 6

room CO_2 concentrations (ppm). Thus, any room CO_2 concentration is comprised of the ambient background concentration, the incremental zonal concentration, and a local incremental concentration from a local source, that is,

$$C_R = 360 + \overline{\Delta C_Z} + \Delta C_\ell \qquad (5)$$

Lastly, the expected change in the CO_2 concentration per person in an individual room is given by

$$\Delta C_R \,/\, \text{person} = \frac{\overline{\Delta C_Z}}{n_z} + \frac{\Delta C_\ell}{n_R} \qquad (6)$$

where n_z and n_R are the number of people in the zone and room, respectively.

The five rooms tested on AC2 had ventilation rates per grill of about 300 m^3/h in 3rd and 4th floor rooms and greater than 1,500 m^3/h per grill in rooms 208A and C. Rooms with 8 and 9 grills, having more occupants, still maintained low projected CO_2 concentrations. The six rooms tested on AC3 also showed differences in apparent ventilation rates per grill--high on the 4th floor (with low estimated CO_2 levels) and low (equal to the AC2 rates on the 3rd and 4th floors) on the third and second floors (with high estimated CO_2 levels). With an estimated 20 people in each of rooms 208A and 323, the estimated CO_2 levels in the latter (with only 4 SA grills versus 9 in the former) were nearly twice (948 ppm) those in the other room (536 ppm). The indoor projected CO_2 concentration is seen to range from 536 to more than 1,000 ppm; more than 600 ppm of CO_2 may indicate the presence of an uncomfortable condition.[4]

Experience from others' measurements of CO_2 levels, ventilation rates, and perceived comfort in buildings will be reviewed in the next section together with an assessment of the results here to suggest areas which would need improvement in the settings of the air handling systems in Gleeson Hall. The appropriate steps for remedial action will be presented.

DISCUSSION

Gleeson Hall Ventilation Tests

A significant amount of air flow information in available in a BNL-AIMS test result as in Tables A1 and A2 in the Appendix. The infiltration rate for each zone is the amount of fresh outside air being supplied to each and, as such, is one potential indication of the level of indoor air quality (IAQ). For ACHs less than 0.5 h^{-1}, IAQ could be poor, especially if occupied by a number of people; for values greater than 1.5 to 2.0 h^{-1}, the likelihood is that IAQ will be acceptable, provided the overall potential pollutant burden or source strength in each zone (including total occupants) is in accord with the ventilation rate and the local pollutant source strength (e.g., ozone from a copier or CO_2 from the local occupants) is also balanced with the local ventilation, for example, an appropriate number of SA grills for the rooms expected occupancy level.

Table 5
Zonal Infiltration Rate, ACH, h^{-1}

	ACH, h^{-1}	
Location	Test 1	Test 2
First Floor	0.23 ± 0.04	---
AC2	2.71 ± 0.52	2.63 ± 0.34
AC3	1.50 ± 0.19	1.74 ± 0.21
AC4	1.98 ± 0.24	2.15 ± 0.26
AC5	5.64 ± 0.76	6.86 ± 0.96

As shown in Table 5 above, with the exception of the first floor result (its mechanical system was not running) measured in Test 1 only, the four AH systems had ACH values exceeding 1.5 h^{-1}; within their respective uncertainties, the results were also identical for both tests.

The west side of the building handled by AC2 might appear to have a higher-than-necessary rate of 2.7 h^{-1} when compared to the 1.6 h^{-1} rate found in the east side (AC3). This excess of 1.1 h^{-1} of ACH with an AC2 zone volume of 4580 m^3 (see Table 1 or Analysis section in Table A1) corresponds to 5040 m^3/h of potentially unnecessary conditioned air. Room 204 (controlled by AC5) also appeared to have a higher-than-necessary rate (there were no occupants over the weekend); if the average value of 6.2 h^{-1} was reduced to 1.6 h^{-1}, the 4.6 h^{-1} savings for the 680-m^3 room (equivalent to 3130 m^3/h excess) would also be significant. Another way to look at this is as follows: the total building volume of 11,100 m^3 at 1.6 h^{-1} is equivalent to a fresh air rate of 17,800 m^3/h; the PFT-measured rate was 27,200 m^3/h or an excess of 9,400 m^3/h.

The potential conditioned-space energy savings may be significant. As a rough rule-of-thumb, at a 0.5 h^{-1} ACH rate, 25% of the heating or cooling requirement in a building is due to ventilation. It can be shown that based on this rule, reducing the whole building ACH from 2.5 h^{-1}, the measured value in this case, down to 1.5 h^{-1}, would save about 30% of the total energy expended at 1.5 h^{-1}, certainly feasible when the building is not occupied, such as on weekends and at night. The question is: What ACH level is needed to assure adequate dilution of occupant-derived CO_2 during the day.

Ventilation and CO_2 Levels in General

The relationship between ventilation and indoor CO_2 levels found by others due to occupants, fundamentally governed by Eq. 1, can be used to put several rules-of-thumb into perspective in order to determine what the ventilation rate and CO_2 levels should be in Gleeson Hall. The following guidelines or observations have been promulgated along with ASHRAE requirements:

Buildings	
Supply Air Rate (suggested):	1.5 cfm/ft^2 with 17% OA
ACHs (observed):	1.0 ± 0.5 h^{-1} of outside air (OA)
Occupancy (suggested):	43 m^3/person or 14 m^2/person
Homes	
Size:	1800 ft^2 (±40%)
ACHs (observed):	0.5 ± 0.2 h^{-1} of OA
Occupancy:	2 adults and 2 children
CO_2 Rate	
Adult:	19 L/h
Child:	12 L/h
ASHRAE[5]	
Minimum Ventilation:	10 L/s • person
Maximum CO_2:	1000 ppm

The expected CO_2 level in a home can be calculated from Eq. 1 ($\Delta C = S/R$) as follows:

$$R = 1800\ ft^2 \times 8\ ft\ ceiling \times 0.02831\ m^3/ft^3 \times 0.5\ h^{-1}\ (ACH)$$

$$= 400\ m^3 \times 0.5\ h^{-1}$$

$$\approx 200\ m^3/h \text{ or } 200{,}000\ L/h$$

$$S = 19\ (2) + 12\ (2) = 62\ L\ CO_2/h$$

$$\Delta C = S/R = 62 \times 10^6/200{,}000 = 310\ ppm$$

$$C = \Delta C + 360\ (CO_2\ ambient) = 670\ ppm$$

The equivalent number of adults generating 62 L CO_2/h is 62/19 or 3.26 persons for an occupancy volume of 400 m^3/3.26 persons or 123 m^3/person or about 3 times the occupancy volume in a commercial building (43 m^3/person).

The expected CO_2 level in a building can also be estimated from the information above:

$$\text{Supply Air } R/V = 1.5\ ft^3/min \cdot ft^2 \times 60\ min/h/8.7\ ft\ ceiling$$

$$= 10.3\ h^{-1}$$

$$\text{Outside Air } R/V = 17\% \text{ of SA} = 10.3\ h^{-1} \times 0.17 = 1.76\ h^{-1}$$

$$S/V = 19{,}000\ mL/h \cdot person/43\ m^3/person$$

$$= 442\ ppm/h$$

$$\Delta C = (S/V)/(R/V) = 442/1.76 = 251\ ppm$$

$$C = \Delta C + 360 = 611\ ppm$$

Thus, roughly speaking, the typical expected indoor CO_2 level in a commercial building, 610 ppm, is about comparable to that in the average home, 670 ppm, because, although the average occupant density is 3 times higher (43 m^3/person versus 123 m^3/person in a home), the outside air rate is more than 3-times higher (1.76 h^{-1} versus 0.5 h^{-1} in a home). It should be mentioned that the high SA rate, 10.3 h^{-1}, is used to assure that temperature and humidity stay within the specified human comfort zone.

These levels ($CO_2 \approx 650$ ppm and $ACH_{Building} \approx 1.8\ h^{-1}$) can be compared with the ASHRAE requirement of 10 L/s • person. The CO_2 concentration equivalent is

$$\Delta C = S/R = 19\ L/h \cdot person \times 10^6/(10\ L/s \cdot person \times 3600) = 528\ ppm$$

$$C = 528 + 360 = 890\ ppm$$

It can be shown that the recommended maximum CO_2 level of 1000 ppm (C = 1000 - 360 = 640 ppm) is equivalent to a CO_2 rate of 23 L/h • person -- about that for an active adult. The equivalent ventilation rate to the ASHRAE value of 10 L/s • person (0.010 m^3/s • person) is ACH = 0.010 m^3/s • person x 3600 s/h/43 m^3/person = 0.84 h^{-1}, that is, about half that of the rule-of-thumb value of 1.76 h^{-1}.

Persily and Dols[3] measured CO_2 in three office buildings; peak zonal CO_2 levels for the buildings as a whole ranged from 400 to 750 ppm, but always below the expected C = S/R values for 43 m^3/person. Local CO_2 levels ranged from 700 to 950 ppm on one floor in Building C which had peak zonal levels of 580 to 750 ppm.

Shaw et al.[4] investigated an 8-story office building which had occupant complaints. Even though ACH values as low as 0.4 h^{-1} were measured by SF_6 tracer decay, the low occupant density of 168 m^3/person gave an equivalent ASHRAE ventilation rate of 18.6 L/s • person (above the guideline) on a total zone or building basis which would give an incremental CO_2 of 19 x 10^6/18.6 x 3600 or ΔC = 284 or C = 360 + 284 + 644 ppm CO_2. In one test with a measured ACH of 0.61 h^{-1} (equivalent to 28.4 L/s • person or ΔC_{CO_2} = 186 and C_{CO_2} = 546 ppm), the mid-morning and mid-afternoon measured CO_2 levels of 500 to 515 ppm were in good agreement with the expected value of 546 ppm. Shaw found that when ACH was reduced such that CO_2 exceeded 520 ppm, the number of occupant complaints increased significantly. These CO_2 levels were averages measured over entire floors or return air (RA) ducts; it is likely that local CO_2 levels may have been much higher in some locations.

In a recent 1994 test,[6] a building with IAQ complaints had an occupancy density of 71 m^3/person with 70 persons per floor and an average mid-day CO_2 level of 680 ppm, well below the ASHRAE maximum of 1000 ppm. Using these steady-state occupancy and CO_2 levels, the estimated ventilation rate was:

$$R = S/\Delta C = 70 \times 19{,}000 \text{ mL/h} \bullet \text{person}/(680 - 360) = 4150 \text{ m}^3\text{/h}$$

or

$$ACH = 4150/4975 = 0.84 \pm 0.08 \text{ h}^{-1}$$

Based on the decay of CO_2 from 730 ppm at 4:30 pm to about 380 ppm by 7:30 pm, a turnover time ($\tau = 1/ACH$) of 1.1 ± 0.15 h or ACH = 0.90 ± 0.12 h^{-1} was estimated, in agreement with the steady-state-derived value above and equivalent to a ventilation rate of 0.90 h^{-1} x 71 m^3/person x 1000 L/m^3/3600 s/h or 17.8 L/s • person.

From these few tests, elsewhere, it appears that perceptions of poor IAQ commenced around CO_2 levels of 550 to 700 ppm -- ~600 ppm, on average. Table 6 below gives expected average zonal CO_2 concentrations based on individual ventilation rates, r_p, that is, flow rate per person:

$$\overline{\Delta C_Z} = \frac{S_{CO_2}}{3600\, r_p} \tag{7}$$

and

$$\overline{C}_Z = 360 + \overline{\Delta C_Z} \tag{8}$$

ACH rates based on individual ventilation rates and occupancy levels are given by:

$$ACH = \frac{3.6\, r_p}{\upsilon_p} \tag{9}$$

It appears that to keep CO_2 levels below about 700 ppm would require an r_p of 15 L/s • person and closer to 20 L/s • person to keep CO_2 near 600 ppm. Of course, as given in Eq. 5, the CO_2 level in a particular room is that above plus any incremental local CO_2 source from individuals in that particular location.

Table 6
Relationship between Ventilation Rate, CO_2 Levels, Occupancy Density, and ACH

Ventilation Rate (r_p), L/s • person	Average Zonal CO_2 Conc., ppm		Building ACH (h^{-1}) at Various Occupancies (υ_p), m^3/person		
	$\overline{\Delta C_Z}$ [1]	$\overline{C}_Z$ [2]	10	40	120
5	1,056	1,416	1.8	0.45	0.15
10	528	890	3.6	0.90	0.30
15	**352**	**712**	**5.4**	**1.35**	**0.45**
20	**264**	**624**	**7.2**	**1.80**	**0.60**
25	211	571	9.0	2.25	0.75

1 Assuming S_{CO_2} = 19 L/h • person
2 Calculated from Eq. 8

Based on a usual occupant density of 40 m^3/person (the middle occupant density column in Table 6), the fresh outside air building ACH should be 1.4 to 1.8 h^{-1} -- a typical value. To provide a higher margin of perceived better IAQ, 25 L/s • person would keep the entire zonal CO_2 concentration at about 570 ppm with a total ACH of 2.25 h^{-1} at 40 m^3/person; this would allow more margin for local incremental CO_2 generation or other potential pollutant sources.

Gleeson Hall Estimated CO_2 Concentrations

During the day, the predicted zonal CO_2 concentrations from the assumed occupancy levels (based on visual inspection of the offices, laboratories, and classrooms) can be compared with that from a suggested occupancy level of 43 m^3/person.[3] For the four zones, Table 7 lists the volumes, the suggested and assumed occupancy levels, and the predicted CO_2 concentrations based on the suggested and assumed occupancy levels.

Table 7
Suggested versus Assumed Occupancy and Predicted CO_2 Levels

					Assumed Occupants		Zonal CO_2 Concentrations, ppm		
							Suggested[3]	Assumed Occupants	
Zone	AH	ACH, h^{-1}	Vol., m^3	Suggested Occupants[1]	Qty.[2]	m^3/per	Occupants	Primary Zone	All Zones
1	AC2	2.63	4,580	106	77	59	543	454	528
2	AC3	1.74	5,100	119	120	43	590	551	606
3	AC4	2.15	740	17	60	12	560	896	940
4	AC5	6.86	680	16	60	11	446	571	606
All Zones			11,100	258	317				581

1 Based on 43 m^3/person
2 Based on visual inspection and assumptions
3 Based on the actual ACH values in each zone

For a suggested occupancy of 43 m^3/person, that is, the occupants uniformly distributed in each zone, but using the actual ACH rates from each zone, the zonal CO_2 levels ranged from 543 to 590 ppm in the first three zones and only 446 ppm in Room 294 (AC5) because of the high ACH rate. It would appear that perceived IAQ would be good at the suggested occupancy desntity -- but this is not how buildings are actually used.

Based on the assumed occupancy levels listed above and in Table 3, the zonal CO_2 concentrations in Table 7 were computed by adding the ambient level (360 ppm) to each of the $\overline{\Delta C_z^{CO_2}}$ in Table 3 under "All Zones"; the primary zone concentration was based on the contribution from occupants in that zone only, that is, 360 plus the maximum value in each zone from Table 3.

For the entire tested portion of the building, the total zonal CO_2 level is estimated to be 581 ppm for the assumed occupancy; this level is almost at the 25 L/s • person level of 571 ppm in Table 6 and, as such, the perceived IAQ should have been good. As an aside, the total infiltration rate from the appendix (27,212 m^3/h for 317 assumed occupants) is equivalent to 23.8 L/s • person.

Looking at the expected CO_2 concentrations by zone, AC2 has the lowest value, AC3 and 5 are the same (606 ppm each), and AC4 is quite elevated; the 940 ppm level is generated almost entirely by the AC4 assumed occupancy in combination with the zone's low ACH resulting in a 896 ppm level due to that zone alone, that is, not CO_2 contributed from other zonal occupants. Clearly, then, AC4 is the only zone from a total zonal basis to possibly be inadequately ventilated when a class of 60 students was present.

Returning to Table 4 with the predicted CO_2 levels computed in the 13 rooms tested with the surrogate PFT source, only the estimated levels (under the column labeled C_R) in rooms handled by AC2 have values less than 600 ppm. Room 444A with 1 SA grill generated 55 ppm CO_2 locally (ΔC_{local}), giving a room concentration of 583 ppm; the occupant had complained of inadequate fresh air but this was not the case during this test. Room 444 with 4 SA grills was not tested (there were complaints here as well) but it is not likely to have had inadequate ventilation either.

The only tested room running on AC2 to have an elevated predicted CO_2 was Room 342. This somewhat larger classroom had only 2 SA grills which did not, at that time, appear to be working (physical inspection) and, indeed, the room had a stuffy feeling. Based on the number of student desks in the room, an estimated occupancy of 8 adults would have generated a room concentration of 706 ppm -- above the cutoff value suggested in this paper of 600 ppm. The high locally-generated CO_2 of 178 ppm from the 8 adults resulted from the locally poor SA rate per grill (430 m^3/h).

The incremental room CO_2 concentration per person, ΔC_R/person, of 25 ppm per person was about the same for the two third floor rooms in Table 4. Thus, the Room 342 high CO_2 concentration was related to the larger number of people in that room. On the other hand, the low ΔC_R/person determined for Rooms 208A and 208C guarantees that those rooms, as operated, could handle their greater occupancy density without reaching a critical CO_2 level. Peculiarly, these teaching dental laboratories had also had air quality complaints. But there is no question that the local ventilation was high, so neither a large number of occupants nor any other pollutant source (such as chemicals used in the lab) should have caused an IAQ problem.

The two rooms tested on the fourth floor controlled by AC3 were large multi-occupancy office areas with moderately low incremental CO_2 concentrations per person with high apparent ventilation rates per grill. The room CO_2 concentrations of 670 ppm were low enough to expect a reasonably good perceived IAQ status. On the other hand, one floor down, Rooms 323 and 339, used as classrooms, had high room CO_2 concentrations, 948 ppm, because of low ventilation rates per grill, and modestly high incremental CO_2 concentrations per person of 19 and 25 ppm/person, respectively. On the second floor, Room 209B, a laboratory in the x-ray suite, had the lowest ventilation rate per grill and one of the highest incremental CO_2 rates per person. Only the low estimated number of occupants, 2, kept the predicted CO_2 level near 700 ppm; each additional person would have raised the CO_2 by 51 ppm. Finally, classroom 213, with about 15 desks, had a high predicted CO_2 concentration (902 ppm) with a high CO_2 level per person (32 ppm/person). Thus, this room could have had a potentially poor IAQ.

The last two AH systems each handled their own individual rooms -- AC4 ran Lecture Room 202 only, and AC5, Lecture Room 204. AC5, with its high ACH rate (6.86 h^{-1}), was operating at a level to keep the CO_2 concentration from 60 people at about 700 ppm or less -- probably good perceived IAQ. AC4, on the other hand, at a rate of 2.15 h^{-1}, would have had the highest CO_2 levels -- over 1000 ppm.

Mitigating Strategies

Both energy conservation and perceived and actual IAQ and occupant comfort are important issues in any building. These PFT test results indicate that there was both a need to reduce ACH during low-occupancy periods to conserve energy and, during the expected normal-occupancy periods, a need to improve both zonal ACH and local ventilation and, possibly, alter room assignment.

Energy conservation measures could be easily accommodated in two time periods. As pointed out earlier in the Discussions, a modest uniform ACH rate of 1.5 h^{-1} in all zones early in the morning, for example, from 6:00 to 8:00 am weekdays, would have provided about a 25% energy savings relative to the 2.5-h^{-1} rate, a level which has been shown to be more than adequate for good perceived IAQ at normal (40 m^3/person) occupant densities (cf., Table 6). Furthermore, late at night and on weekends, a roll-back to 0.5 h^{-1} would certainly provide sufficient fresh air to the few occupants that might be present and would reduce energy consumption by 50%; a modest temperature set-back (in the winter) would provide an additional 10% savings.

Perceived indoor air quality improvement requires consideration of the total zonal occupant burden and the individual rooms' occupant levels and supply air (SA) availability. As was pointed out in Table 7, based on the assumed occupancy levels on a total zonal basis, three of the four zones had sufficient overall fresh air; AC2 was perfect (only 528 ppm of CO_2 predicted) and AC3 and AC5 could have benefitted from slightly higher ventilation rates. However, AC4, assuming 60 student present in the lecture room, should have had a much higher outside air ACH rate.

If the total occupancy level was the same as assumed in Table 3, it could be shown that the following adjustments to total zonal ventilation would reduce the incremental zonal CO_2 levels to about 160 ppm in each zone during the daytime occupied periods:

	ACH, h^{-1}	
AH	Before	After
AC2	2.63	2.6
AC3	1.74	2.7
AC4	2.15	9
AC5	6.86	9.5

The remaining steps to be taken require examining the local CO_2 response and the number of SA grills. On AC2, Room 444A will be fine with 1 occupant; this was a single office. Room 341, a secretarial area, would be acceptable with 2 or 3 occupants. Room 342, a classroom with only 2 grills working at poor capacity, requires correcting the SA setting and adding at least 1 (preferably 2) new SA grills; this would reduce the incremental CO_2 concentration per person to about 5 to 7 ppm/person. Rooms 208A and 208C were acceptable as is.

After adjustment of AC3 from 1.7 to 2.7 h^{-1} during daytime occupancy, three of the 6 rooms tested in that zone would need further individual adjustment. Classroom 323 had a sufficient number of SA grills (4) for its small size, but to support an estimated 20 students, the local fresh air rate from each needed to be tripled. Classroom 339 with only 3 SA grills had a higher incremental CO_2 value (25 ppm/person compared to 19 ppm/person for Room 323). Thus, both an additional SA grill was needed and the rate from each needed to be increased 2.5-fold; with these changes, both rooms 323 and 339 would have had CO_2 levels at about 600 ppm. Lastly, the small Room 213 either needed to be re-assigned as a 1- or, at most, 2-person office or an extra SA grill installed and the delivery rate increased 2.5-fold.

Rooms 202 and 204 would be fine for 60 occupants each with just the increase in total outside air ACH to 9 h^{-1}.

Recommendations

Now that the reconstruction work on Gleeson Hall has been completed, retesting should be done to compare the ventilation rate and the predicted CO_2 levels. In addition to the testing that was performed 2 years ago, the ventilation rate of the perimeter rooms should be checked and more rooms, if not all rooms, on the AH systems should be tagged with the surrogate PFT source to check all local ventilation rates. Where possible, local CO_2 measurements should be made to confirm the reliability of the prediction capabilties of this technology.

The techniques employed in these tests and the results should be critically reviewed by the college staff for their assessment of the utility of the approach, in part to determine if the technology should be made more widely available and, in part, to set up student participation in the advancement of the implementation and interpretation of the PFT technology as a ventilation engineer's tool.

CONCLUSIONS

As a result of performing two several-day BNL-AIMS passive device ventilation tests, both the zonal and local ventilation performance of a significant portion of the Gleeson Hall building was satisfactorily performed. The ventilation rates determined for the four operating air handling (AH) systems, AC2 to AC5, were identical in both tests and ranged from about 1.5 to 6.8 h^{-1}.

In the second test, the use of a distributed PFT source as a surrogate for occupants who normally expire CO_2 was able to quantify the effectiveness of local (individual rooms) ventilation in combination with total zonal ventilation to arrive at a reliable predicted CO_2 concentration in each location tested (13 rooms); CO_2 concentrations were predicted to range from 536 to 1003 ppm.

A review of some published building ventilation studies during which CO_2 measurements and perceived air quality were noted plus some private communications and assessment of ASHRAE guidelines resulted in the observation that indoor CO_2 concentrations from occupants should, in general, be less than 600 ppm to assure a good perceived IAQ and that to achieve these desired conditions over an entire zone serviced by a given AH system, would require a fresh air ventilation rate of 20 to 25 L/s • person which, at an occupancy level of 40 m^3/person, is equivalent to an ACH rate of 1.8 to 2.2 h^{-1}.

During these two tests in Gleeson Hall, the ACH rates were constant and identical for Test 1 over a 2-day weekday period and for Test 2 over a 3-day weekend period. From an IAQ (indoor air quality) standpoint, it was determined that during the day, based on the assumed occupancy, AC2 was running at the right rate (2.6 h^{-1}), AC3 needed to be increased from 1.7 to 2.7 h^{-1}, and ACs 4 and 5 from 2.2 and 6.8 h^{-1}, respectively, to about 9 h^{-1}. However, at night and on weekends, from an energy conservation perspective, all four AH systems should be reduced to 0.5 h^{-1} and the temperature set-back as well (in the winter time) for an estimated 60% energy savings during the five 8-h periods during the week and two 24-h periods on the weekend (equivalent to a weekly energy savings of about 30%).

Locally poor ventilation, that is, not associated with the AH system as a whole, was identified as significant in 4 of 11 rooms tested -- 1 of 5 tested, running on AC2, and 3 of 6 tested running on AC3. Improvement in local ventilation required that 3 of the 4 add 1 or 2 extra supply air (SA) grills and increase the fresh air rate from each by 2- to 3-fold; the fourth room required the SA rate to be tripled.

ACKNOWLEDGMENTS

Thanks are extended to Jay Fraser of Integrated Innovation for arranging for the testing at the SUNY Farmingdale campus and for assistance in the field implementation, to John Tiedeman, a professor in the HVAC engineering department, for helpful discussions, and to Randy Schnittger, the buildings HVAC operator, for access to locked areas in the building and for suggestions on access points in the AH ductwork for source deployment. Thanks also go to DOE OHER for their fundamental support of the PFT technology at Brookhaven and to DOE ER Laboratory Technology Transfer Program for support in writing the report for this technology demonstration.

REFERENCES

1. 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.

2. 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).

3. Persily, A. and Dols, W. S. The relation of CO_2 concentration to office building ventilation. In Air Change Rate and Airtightness in Buildings, ASTM STP 1067, M. H. Sherman, Ed., pp. 77-92, American Society for Testing and Materials, Philadelphia, 1990.

4. Shaw, C. Y., Magee, R. J., Shirtliffe, C. J., and Unligil, H. Indoor air quality assessment in an office-library building: Part II - Test results. ASHRAE Tech. Data Bull. 7 (4), 8-17 (1991).

5. Ventilation for acceptable indoor air quality. ASHRAE Standard 62-1981R, American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc., 1986.

6. Prezant Associates, Inc., private communication, 1994.

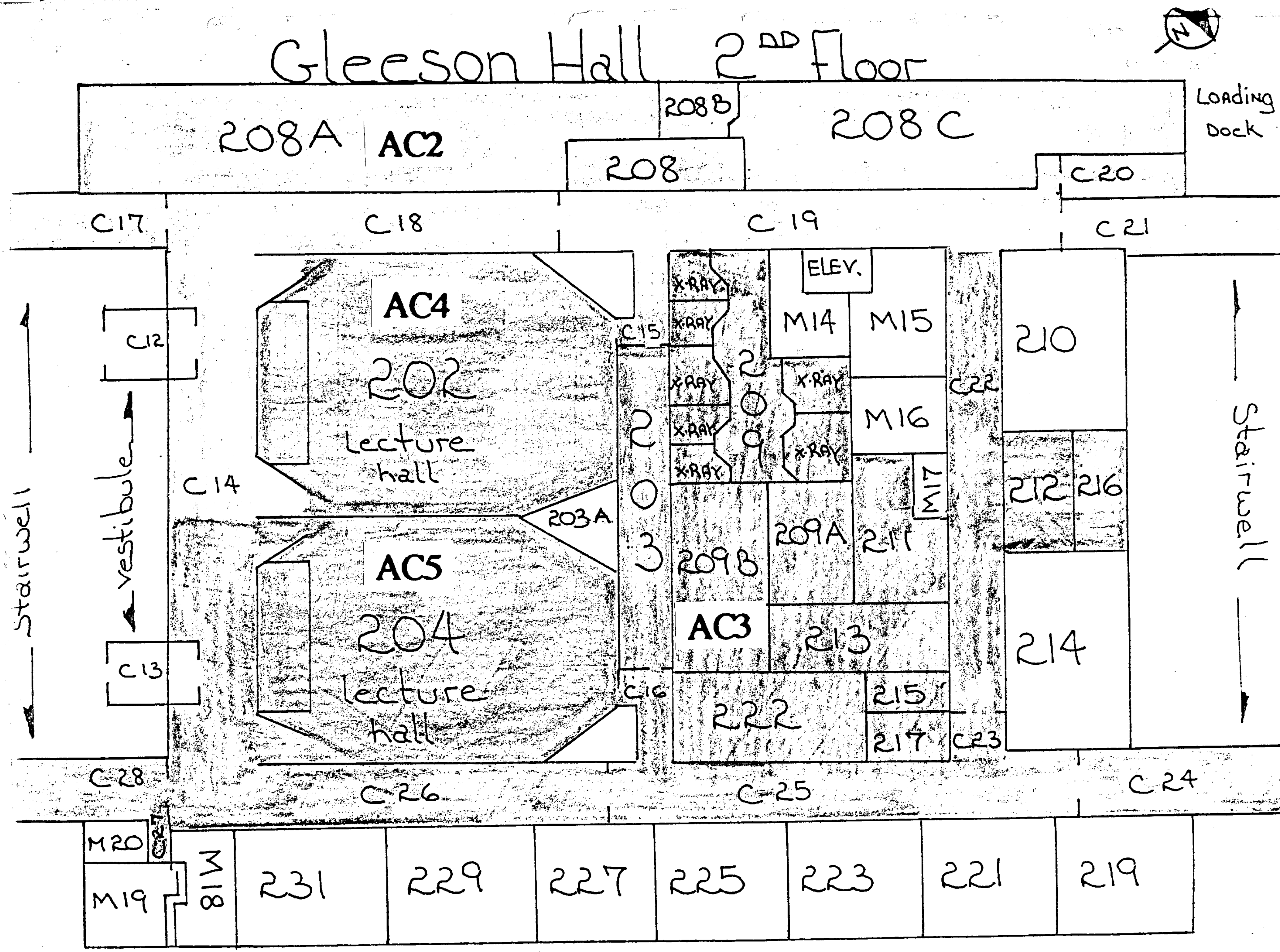
Gleeson Hall 2nd Floor
N
Loading Dock
208A
AC2
208B
208C
208
C20
C17
C18
C19
C21
AC4
202
lecture hall
C12
C13
vestibule
Stairwell
C14
C15
203
203A
AC5
204
lecture hall
C16
X-RAY
209
ELEV.
M14
M15
M16
M17
209A
209B
211
AC3
213
222
215
217
C22
C23
210
212
216
214
C28
C26
C25
C24
M20
C27
M19
M18
231
229
227
225
223
221
219

Figure 1

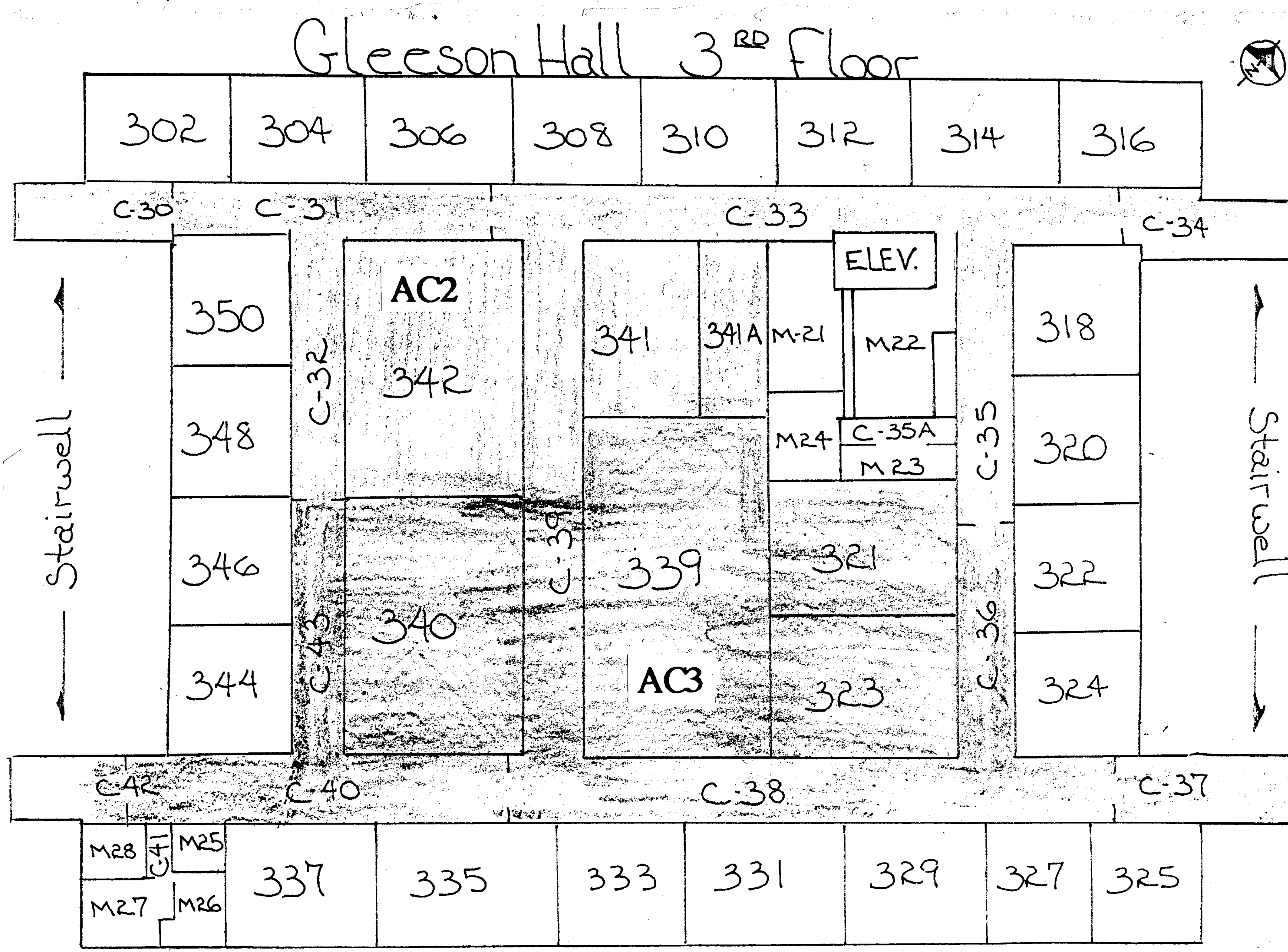
Gleeson Hall 3RD Floor
302
304
306
308
310
312
314
316
C-30
C-31
C-33
C-34
AC2
342
341
341A
M-21
M22
ELEV.
C-35A
M23
M24
C-35
318
320
322
324
Stairwell
Stairwell
350
348
346
344
C-32
C-43
340
C-39
339
AC3
321
323
C-36
C-42
C-40
C-38
C-37
M28
C-41
M25
M27
M26
337
335
333
331
329
327
325

Figure 2

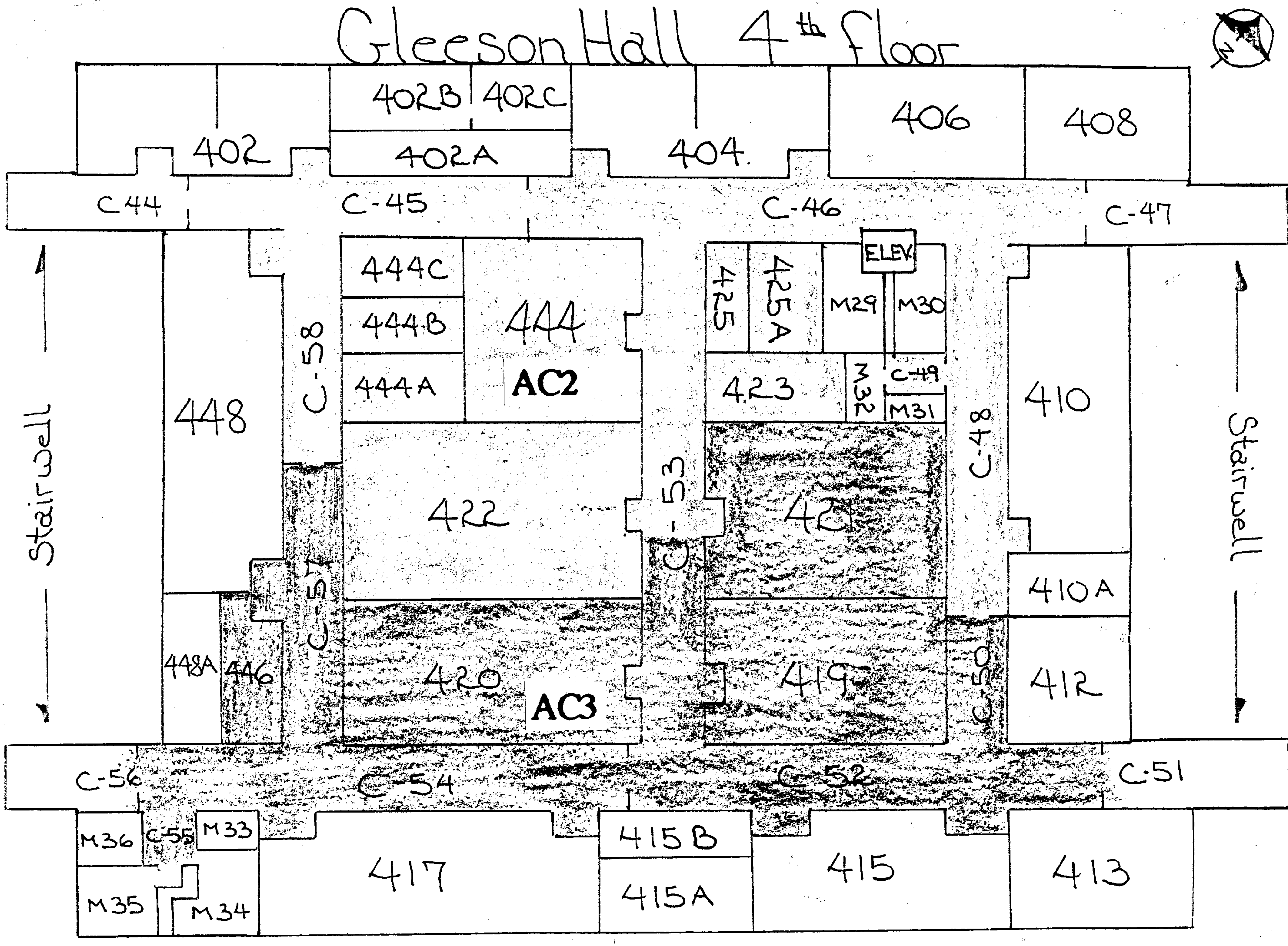
Gleeson Hall 4th floor
N
402
402B
402C
402A
404
406
408
C-44
C-45
C-46
C-47
Stairwell
448
448A
446
444C
444B
444A
444
AC2
422
420
AC3
C-58
C-57
C-53
425
425A
ELEV.
M29
M30
423
M32
C-49
M31
421
419
C-48
C-50
410
410A
412
Stairwell
C-56
C-54
C-52
C-51
M36
C-55
M33
M35
M34
417
415B
415A
415
413

Figure 3

APPENDIX A

Detailed BNL-AIMS Test Reports

Table A1

BNL-AIMS

08:51:50 05-07-1993

PROJECT: SUNY FARMINGDAL START: 12:40 (04-07-1993) Wed BNL CODE: 8020A0
HOUSE:GLEESON HALL STOP: 10:00 (04-09-1993) Fri ANALYZED: 03-31-1993

************************************ RATES ************************************

OVERALL INFILTRATION RATE = 27186.7 ± 2126.4(m^3/h)
OVERALL AIR EXCHANGE RATE = 1.409 ± 0.117(1/h)

ZONE	ZONE LOCATION	SOURCE RATE @25C (nL/m)	QTY	SOURCE RATE @T (nL/h)	EXFILTRATION RATE (m^3/h)	EXFILTRATION SD (m^3/h)	INFILTRATION RATE (m^3/h)	INFILTRATION SD (m^3/h)	INFILTRATION ACH (/h)	INFILTRATION SD (/h)
1	1ST FLOOR	6.9	14	5088	2716.2	538.7	1854.3	330.4	0.226	0.042
2	AC2	35.7	3	5773	13633.5	2144.1	12403.6	2315.7	2.708	0.523
3	AC3	25.3	5	6667	7017.1	1553.4	7626.3	869.2	1.495	0.186
4	AC4	8.8	3	1389	469.7	268.7	1467.0	161.2	1.982	0.239
5	AC5	5.2	6	1541	3350.2	1548.1	3835.5	482.4	5.640	0.763

ZONE-ZONE	RATE	± SD (m^3/h)
1 - 2	804.6	175.9
1 - 3	344.0	61.7
1 - 4	86.5	14.9
1 - 5	118.6	21.7
2 - 3	3107.4	407.8
2 - 4	439.3	64.5
2 - 5	327.2	79.0
3 - 4	155.5	34.5
3 - 5	403.2	74.3
4 - 5	72.0	25.5

ZONE-ZONE	RATE	± SD (m^3/h)
2 - 1	837.4	170.5
3 - 1	591.7	150.2
4 - 1	607.2	128.4
5 - 1	179.3	131.8
3 - 2	3980.5	1213.5
4 - 2	577.9	164.6
5 - 2	578.2	1948.6
4 - 3	383.0	62.0
5 - 3	687.3	350.2
5 - 4	-38.5	46.9

TOTAL FLOW IN OR OUT

ZONE	RATE	± SD (m^3/h)	ACH	± SD(/h)
1	4069.8	639.3	0.496	0.082
2	18344.8	2319.4	4.005	0.545
3	12148.0	1287.0	2.382	0.279
4	2109.8	219.6	2.851	0.329
5	4756.4	593.9	6.995	0.941

************************************ ANALYSIS ************************************

ZONE	VOL m^3	SOURCE TYPE	AVG.TRACER CONC. (pL/L) ± SD: ocPDCH	PMCP	PMCH	ptPDCH	T-PTCH
1	8200	ocPDCH	1.286 ± 0.151	0.098 ± 0.006	0.129 ± 0.014	0.113 ± 0.014	0.021 ± 0.007
2	4580	PMCP	0.073 ± 0.006	0.343 ± 0.024	0.139 ± 0.033	0.034 ± 0.005	0.016 ± 0.034
3	5100	PMCH	0.060 ± 0.002	0.095 ± 0.001	0.594 ± 0.017	0.034 ± 0.002	0.023 ± 0.002
4	740	ptPDCH	0.072 ± 0.003	0.082 ± 0.004	0.077 ± 0.003	0.672 ± 0.019	0.000 ± 0.000
5	680	T-PTCH	0.043 ± 0.001	0.035 ± 0.004	0.064 ± 0.005	0.018 ± 0.003	0.328 ± 0.024

Table A1 cont'd **CONCENTRATION(pL/L)**

	CATS0	ocPDCH	PMCP	PMCH	ptPDCH	T-PTCH	PDCB	mmPDCH	opPDCH	mPDCH	2-PTCH		
1	9510	1.208	0.090	0.118	0.100	0.016	0.000	1.273	0.000	1.273	0.000		
1	4622	1.445	0.097	0.123	0.109	0.031	0.000	1.519	0.000	1.519	0.000		
1	6095	1.115	0.102	0.127	0.111	0.015	0.000	1.207	0.000	1.207	0.000		
1	5017	1.377	0.104	0.149	0.132	0.022	0.000	1.399	0.000	1.399	0.000		
1	11410	0.574	0.047	0.072	0.035	0.000	0.000	0.579	0.000	0.585	0.000	DELETED	M7
2	3236	0.101	0.314	0.202	0.034	0.012	0.000	0.125	0.000	0.130	0.000	DELETED	C46
2	11187	0.152	0.245	0.238	0.038	0.007	0.000	0.184	0.000	0.191	0.000	DELETED	C48
2	4962	0.075	0.353	0.119	0.033	0.000	0.000	0.100	0.000	0.103	0.000		444
2	0320	0.060	0.352	0.117	0.029	0.005	0.000	0.096	0.000	0.100	0.000		444A
2	9410	0.079	0.145	0.255	0.037	0.011	0.000	0.095	0.000	0.098	0.000	DELETED	C33
2	10476	0.077	0.313	0.168	0.039	0.000	0.000	0.000	0.123	0.128	0.000		341
2	4803	0.075	0.328	0.190	0.040	0.007	0.000	0.000	0.107	0.111	0.000		342
2	6753	0.074	0.313	0.168	0.001	0.008	0.000	0.000	0.141	0.146	0.000	DELETED	C19
2	11132	0.063	0.333	0.111	0.028	0.086	0.000	0.000	0.085	0.088	0.000		208A
2	0679	0.079	0.381	0.129	0.035	0.000	0.000	0.109	0.000	0.113	0.000		208C
3	3021	0.061	0.096	0.589	0.037	0.024	0.000	0.000	0.091	0.094	0.000		419
3	2271	0.060	0.096	0.621	0.037	0.025	0.000	0.000	0.088	0.091	0.000		420
3	10716	0.060	0.097	0.581	0.035	0.023	0.000	0.000	0.083	0.086	0.000		421
3	7200	0.048	0.073	0.415	0.027	0.016	0.000	0.000	0.091	0.095	0.000	DELETED	C38
3	0302	0.057	0.094	0.590	0.033	0.022	0.000	0.000	0.082	0.085	0.000		323
3	11665	0.059	0.093	0.572	0.033	0.024	0.000	0.000	0.085	0.088	0.000		339
3	958	0.062	0.097	0.609	0.034	0.020	0.000	0.000	0.088	0.091	0.000		209
3	5522	0.058	0.094	0.581	0.032	0.022	0.000	0.000	0.083	0.086	0.000		209B
3	3701	0.061	0.095	0.609	0.032	0.027	0.000	0.000	0.085	0.089	0.000		213
4	5994	0.069	0.083	0.078	0.658	0.000	0.000	0.000	0.675	0.675	0.000		202 front
4	3912	0.073	0.085	0.079	0.694	0.000	0.000	0.000	0.715	0.715	0.000		mid
4	0977	0.073	0.077	0.074	0.665	0.000	0.000	0.000	0.679	0.679	0.000		back
5	5830	0.045	0.033	0.063	0.021	0.347	0.000	0.062	0.000	0.064	0.000		204 front
5	9356	0.042	0.033	0.060	0.015	0.336	0.000	0.000	0.055	0.058	0.000		mid
5	5387	0.043	0.040	0.070	0.019	0.301	0.000	0.000	0.064	0.066	0.000		back

C.F.:	PDCB	PMCP	PMCH	ocPDCH	ptPDCH	mPDCH	PTCH	COEFFICIENTS FILE
	0.94	0.94	0.92	1.05	0.92	0.65	0.95	6B160

```
**************************************** NOTES ****************************************
All gas volumes are reported at 25 C. and 1 atm.
The standard deviation in the source strength has been set at  10 %.
The standard deviation in the volume measurement has been set at  5 %.
The overall normalized condition number (K(C)/N^1.5)=   0.502
K(DC)/N =  1.122
Zonal condition numbers are:
ZONE                   1          2          3          4          5
Condition Number     1.078      1.239      1.191      1.065      1.024

                  FLOW-RATIOS  STD.DEV.

INFILTRN/EXFILTRN
ZONE  1               0.683     0.0543
ZONE  2               0.910     0.1381
ZONE  3               1.087     0.1610
ZONE  4               3.124     0.8935
ZONE  5               1.145     0.5036
INTERZONAL
1- 2/ 2- 1            0.961     0.2154
1- 3/ 3- 1            0.581     0.1492
1- 4/ 4- 1            0.142     0.0295
1- 5/ 5- 1            0.662     0.4864
2- 3/ 3- 2            0.781     0.2331
2- 4/ 4- 2            0.760     0.2295
2- 5/ 5- 2            0.566     1.9063
3- 4/ 4- 3            0.406     0.1107
3- 5/ 5- 3            0.587     0.3151
4- 5/ 5- 4           -1.869     2.3502
STANDARD DEVIATION OF T-PTCH IN ZONE 1 IS GREATER THAN 25 %
STANDARD DEVIATION OF T-PTCH IN ZONE 2 IS GREATER THAN 25 %
```

Table A2

BNL—AIMS 09:02:14 05-07-1993

PROJECT: SUNYFARMINGDALE START: 10:15 (04-09-1993) Fri BNL CODE: 8021A0
HOUSE: GLEESON HALL STOP: 10:50 (04-12-1993) Mon ANALYZED: 04-01-1993

************************************ RATES ************************************

OVERALL INFILTRATION RATE = 27212.3 ± 1751.7(m^3/h)
OVERALL AIR EXCHANGE RATE = 2.452 ± 0.175(1/h)

ZONE	ZONE LOCATION	SOURCE RATE @25C (nL/m)	QTY	@T (nL/h)	EXFILTRATION RATE (m^3/h)	EXFILTRATION SD (m^3/h)	INFILTRATION RATE (m^3/h)	INFILTRATION SD (m^3/h)	INFILTRATION ACH (/h)	INFILTRATION SD (/h)
1	AC2	35.7	3	5773	12987.7	1749.9	12058.0	1451.9	2.633	0.343
2	AC3	25.3	5	6667	8233.4	1539.6	8899.7	976.0	1.745	0.210
3	AC4	8.8	3	1389	1009.5	398.4	1589.3	171.6	2.148	0.256
4	AC5	5.2	6	1541	4981.8	700.6	4665.3	609.4	6.861	0.960

ZONE-ZONE	RATE	± SD (m^3/h)
1 - 2	2929.5	340.1
1 - 3	398.1	44.9
1 - 4	290.9	48.8
2 - 3	145.5	27.3
2 - 4	395.5	67.6
3 - 4	83.2	15.9

ZONE-ZONE	RATE	± SD (m^3/h)
2 - 1	3945.3	983.5
3 - 1	678.6	418.6
4 - 1	-75.7	164.7
3 - 2	384.8	93.5
4 - 2	505.5	110.5
4 - 3	23.2	28.0

TOTAL FLOW IN OR OUT

ZONE	RATE	± SD (m^3/h)	ACH	± SD(/h)
1	16606.1	1760.1	3.626	0.425
2	12719.6	1382.0	2.494	0.298
3	2156.1	229.2	2.914	0.342
4	5434.8	708.6	7.992	1.116

************************************ ANALYSIS ************************************

ZONE	VOL m^3	SOURCE TYPE	AVG. TRACER CONC. (pL/L) ± SD PMCP	PMCH	ptPDCH	T-PTCH
1	4580	PMCP	0.372 ± 0.011	0.135 ± 0.028	0.033 ± 0.016	0.002 ± 0.003
2	5100	PMCH	0.089 ± 0.002	0.559 ± 0.021	0.028 ± 0.002	0.012 ± 0.002
3	740	ptPDCH	0.075 ± 0.001	0.063 ± 0.001	0.653 ± 0.023	0.004 ± 0.004
4	680	T-PTCH	0.028 ± 0.002	0.049 ± 0.004	0.014 ± 0.001	0.285 ± 0.024

Table A2 cont'd **CONCENTRATION(pL/L)**

Zone	Location	CATS#	PMCP	PMCH	ptPDCH	T-PTCH	PDCB	ocPDCH	ooPDCH	mpPDCH	mPDCH	2-PTCH		
1	C46	6589	0.265	0.195	0.020	0.005	0.000	0.144	0.152	0.000	0.158	0.000	DELETED	
1	C48	8690	0.230	0.271	0.022	0.005	0.000	0.126	0.144	0.000	0.150	0.000	DELETED	
1	444	5912	0.351	0.113	0.022	0.000	0.000	0.107	0.126	0.000	0.131	0.000		
1	444G	2950	0.536	0.448	0.069	0.010	0.000	0.218	0.256	0.000	0.264	0.000	DELETED	
1	444A	2464	0.376	0.133	0.030	0.000	0.000	1.257	1.285	0.000	1.285	0.000		
1	C33	8014	0.114	0.201	0.014	0.000	0.000	0.087	0.101	0.000	0.105	0.000	DELETED	Near elevator shaft (diluted)
1	341	2928	0.368	0.190	0.065	0.000	0.000	0.614	0.723	0.000	0.723	0.000		
1	342	4517	0.382	0.128	0.030	0.004	0.000	0.608	0.617	0.000	0.617	0.000		
1	342G	5359	0.427	0.143	0.030	0.000	0.000	0.306	0.321	0.000	0.327	0.000	DELETED	Biased by room air - stuffy room (little air flow)
1	C19	6434	0.294	0.194	0.028	0.007	0.000	0.134	0.156	0.000	0.162	0.000	DELETED	
1	208A	4759	0.373	0.119	0.026	0.006	0.000	0.182	0.188	0.000	0.195	0.000		
1	" G	7369	0.491	0.160	0.029	0.007	0.000	0.149	0.174	0.000	0.181	0.000	DELETED	
1	208C	2797	0.381	0.128	0.026	0.000	0.000	0.200	0.214	0.000	0.222	0.000		
2	419	11389	0.087	0.527	0.028	0.011	0.000	0.395	0.403	0.000	0.404	0.000		
2	" G	3403	0.099	0.609 (.541)	0.029 (.026)	0.016 (.014)	0.000	0.266 (.236)	0.278	0.000	0.286	0.000	DELETED	
2	420	7250	0.092	0.598	0.024	0.014	0.000	0.171	0.186	0.000	0.193	0.000		
2	421	9470	0.089	0.557	0.029	0.012	0.000	0.375	0.383	0.000	0.385	0.000		
2	C38	2787	0.064	0.379 (.527)	0.020 (.028)	0.011 (.015)	0.000	0.118 (.164)	0.132	0.000	0.137	0.000	DELETED	
2	323	7239	0.088	0.555	0.028	0.014	0.000	0.546	0.553	0.000	0.553	0.000		
2	339	8647	0.092	0.572	0.030	0.011	0.000	0.653	0.662	0.000	0.662	0.000		
2	" G	8739	0.088	0.557	0.025	0.013	0.000	0.202	0.209	0.000	0.217	0.000	DELETED	
2	209	6674	0.080	0.559	0.027	0.011	0.000	0.433	0.445	0.000	0.445	0.000		
2	209a	11570	0.089	0.565	0.030	0.014	0.000	1.146	1.133	0.000	1.133	0.000		
2	" G	2402	0.100	0.652 (.574)	0.032 (.028)	0.015 (.013)	0.000	0.496 (.486)	0.510	0.000	0.510	0.000	DELETED	Biased by room air
2	213	7052	0.087	0.539	0.027	0.009	0.000	0.782	0.800	0.000	0.800	0.000		
3	202	8891	0.074	0.063	0.630	0.006	0.000	0.253	0.000	0.864	0.864	0.000		
3	"	5748	0.075	0.063	0.652	0.007	0.000	0.226	0.000	0.856	0.856	0.000		
3	"	4071	0.076	0.064	0.676	0.000	0.000	0.232	0.000	0.886	0.886	0.000		
3	" G	2000	0.096	0.081	0.897 (.757)	0.000	0.000	0.267	0.000	1.144	1.144	0.000	DELETED	
3	" G	5499	0.081	0.068	0.723	0.000	0.000	0.225	0.000	0.926	0.926	0.000	DELETED	
4	204	8424	0.029	0.053	0.014	0.305	0.000	0.226	0.225	0.000	0.234	0.000		
4	"	5338	0.026	0.047	0.013	0.291	0.000	0.231	0.231	0.000	0.240	0.000		
4	"	4503	0.027	0.047	0.015	0.258	0.000	0.174	0.179	0.000	0.186	0.000		
4	" G	3923	0.031	0.056	0.013	0.121	0.000	0.107	0.119	0.000	0.123	0.000	DELETED	
4	" G	9006	0.032	0.054	0.014	0.114	0.000	0.094	0.107	0.000	0.111	0.000	DELETED	

C.F.:	PDCB	PMCP	PMCH	ocPDCH	ptPDCH	mPDCH	PTCH	COEFFICIENTS FILE
	0.94	0.94	0.92	1.05	0.92	0.65	0.95	6B160

************************************ NOTES ************************************

All gas volumes are reported at 25 C. and 1 atm.
The standard deviation in the source strength has been set at 10 %.
The standard deviation in the volume measurement has been set at 5 %.
The overall normalized condition number (K(C)/N^1.5)= 0.543
K(DC)/N = 1.086
Zonal condition numbers are:

ZONE	1	2	3	4
Condition Number	1.155	1.138	1.035	1.009

	FLOW-RATIOS	STD.DEV.
INFILTRN/EXFILTRN		
ZONE 1	0.928	0.0659
ZONE 2	1.081	0.1201
ZONE 3	1.574	0.5114
ZONE 4	0.936	0.0271
INTERZONAL		
1- 2/ 2- 1	0.743	0.1890
1- 3/ 3- 1	0.587	0.3636
1- 4/ 4- 1	-3.843	8.3622
2- 3/ 3- 2	0.378	0.1155
2- 4/ 4- 2	0.782	0.1925
3- 4/ 4- 3	3.581	4.3513

STANDARD DEVIATION OF ptPDCH IN ZONE 1 IS GREATER THAN 25 %
STANDARD DEVIATION OF T-PTCH IN ZONE 1 IS GREATER THAN 25 %
STANDARD DEVIATION OF T-PTCH IN ZONE 3 IS GREATER THAN 25 %