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A STUDY OF DIESEL FUME ENTRAINMENT IN AN OFFICE BUILDING

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ABSTRACT

The authors used a tracer gas technique to study diesel fume entrainment into a high-rise office building where the tenants of the building have had a history of health-related complaints. The primary symptoms reported by the building tenants included headache and nausea. In addition, tenants reported noticing a strong diesel odor at various times and days of the week. The building is situated in the downtown area of a large city and directly over an underground train station. Diesel emissions from the underground trains parked at the station are vented to street level through a series of steel grates in the sidewalk. The outdoor air inlet associated with the building ventilation system serving the area with the health complaints is situated on the building wall 10 ft above the sidewalk and is directly above one of these exhaust grates. We simultaneously measured the indoor and outdoor concentrations of carbon monoxide and nitrogen oxides during the afternoon commute period. The indoor concentrations of carbon monoxide ranged from 5 to 14 ppm. The outdoor concentration of carbon monoxide in the vicinity of the outside air inlet peaked at 50 ppm during train movement.

The indoor concentrations of nitrogen dioxide ranged from < 0.05 ppm to 0.25 ppm. The outdoor concentration of nitrogen dioxide in the vicinity of the outside air inlet was observed to average 0.65 ppm over a two-hour measurement period. We used a tracer gas technique to determine the percent of sidewalk exhaust emissions entering the building. We injected sulfur hexafluoride gas at a constant flow rate into three of the exhaust grates and collected both instantaneous syringe samples and time-integrated bag samples at indoor locations, the outside air duct, and at an outdoor location in the vicinity of the outside air inlet. We used a gas chromatograph with an electron capture detector to measure the tracer gas concentrations over a range of 0.1 ppb to 50 ppb. We computed the total entrainment of the sidewalk exhaust to be 5.8% and 4.5% for a consecutive pair of tests. We also calculated the entrainment through the outside air inlet to be 0.6% and 0.4%, which is just 10% of the total building entrainment, suggesting that entrainment from other routes is significant.

INTRODUCTION

This study was prompted by complaints from the first- and second-floor tenants of an odor of diesel emissions in the building. A concern was expressed that the emissions coming from the underground railroad trains through the sidewalk exhaust grates may be entering the building ventilation system outside air intake. We decided to measure selected contaminants which are typical components of diesel exhaust (e.g., CO and NO_x) and to conduct a tracer gas test to quantify the amount of the diesel train exhaust emissions entering the building from these sidewalk grates.

The site is a high-rise office building located in the downtown area of a large city. The building is a 12-story structure and is situated directly over an underground train station. The gross area of each floor is approximately 23,000 ft². The first and second floors are predominantly office space.

The building ventilation system serving the first floor and mezzanine office areas has an outside air inlet located on the side of the building. The outside air inlet is approximately 10 ft above the sidewalk where the underground train station sidewalk exhaust grates are located. The outside air intake is a 5 ft by 12 ft screened and louvered opening which is located in a mezzanine-level mechanical room. Several ventilation systems have outside air ducts connected to this opening. We measured the airflow rate entering the outside air duct serving the first floor and mezzanine area (using a hot wire anemometer) to be 310 ft³ per minute. The second-floor area is serviced by a separate building ventilation system with outside air intakes located on the opposite side of the building.

FUME ENTRAINMENT MEASUREMENT PROTOCOL

We used a tracer gas technique to quantify the amount of train diesel emissions coming from the sidewalk exhaust grates into the building. We installed 1/4-in-diameter polyethylene tubing to inject sulfur hexafluoride gas into each of three sidewalk exhaust grates near the outside air inlet. These exhaust grates are located directly beneath and to the left and right of the outside air intake supplying air to the first-floor and mezzanine office areas. We set the total tracer gas injection rate at 5 liters per minute of 1% sulfur hexafluoride gas. We injected the tracer gas into three sidewalk exhaust grates for a period of approximately one hour, during which time we collected air samples at various indoor and outdoor locations. Figure 1 depicts the locations of the outside air intakes, sidewalk exhaust grates, and the outdoor and first-floor air sampling points. Figure 2 depicts the mezzanine level of the first floor and the outside air duct sample location in the mechanical room. Figure 3 depicts the location of the second-floor sample locations. Sample location 1 was located outdoors directly beneath the outdoor air inlet. Sample location 2 was located in the outside air duct located in the mechanical room of the first floor/mezzanine level ventilation system. Sample location 3 was located in the southwest side of the first floor and sample location 4 was located by a revolving door. Samples locations 5 and 6 were on the west side and east side of the second floor, respectively. We col-

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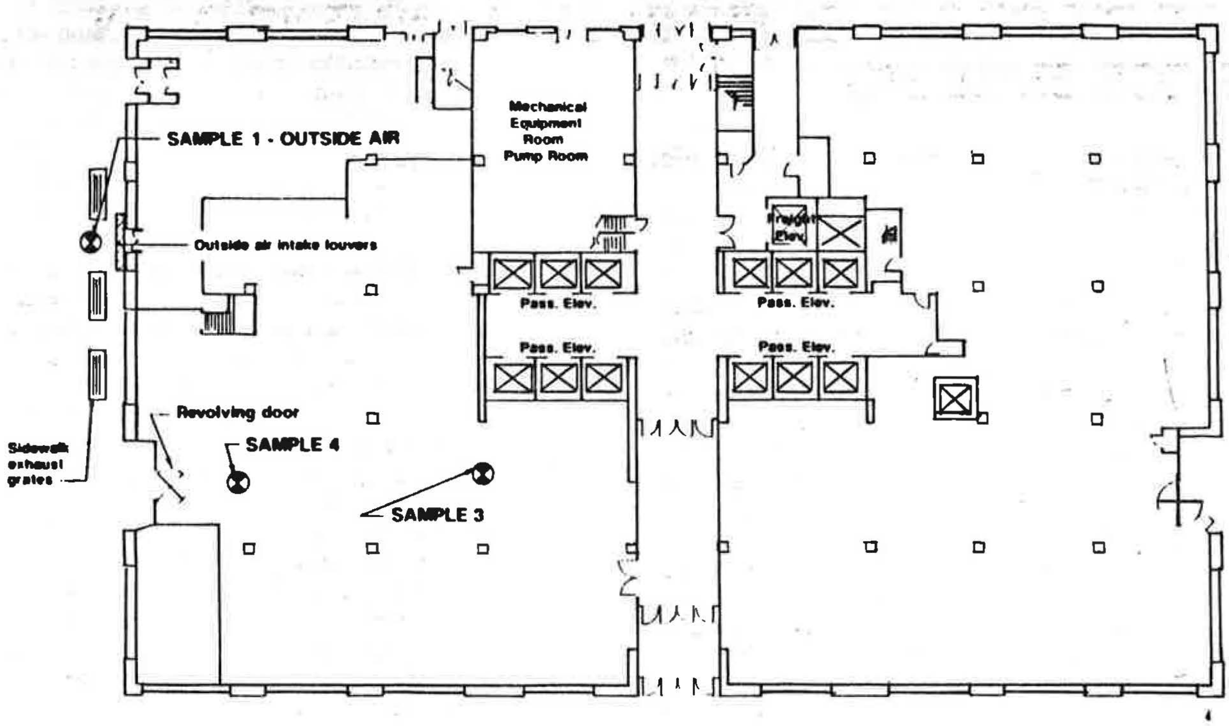

Figure 1 *Floor plan of the first floor depicting the locations of the outside air intakes, sidewalk exhaust grates, and the outdoor and first-floor air-sampling points*

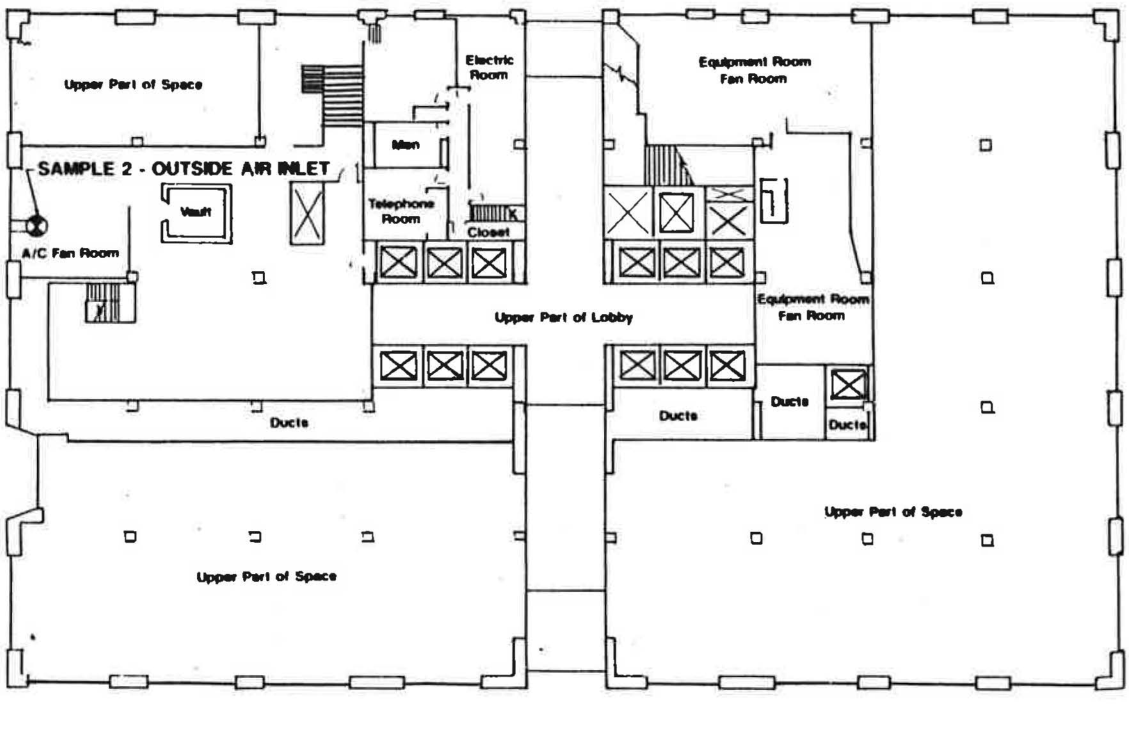

Figure 2 *Floor plan of the mezzanine level depicting the mechanical room location and the outside air duct sample location*

lected background air samples at each location before each test.

Following the start of the tracer injection we collected grab samples at each location at approximately 15-minute intervals. In addition, we installed a sample bag to continuously collect air from the outside air inlet during each test. We analyzed the samples on-site and later off-site using a gas chromatograph with an electron capture detector calibrated over a 0.1 to 50 ppb range.

We used the following formulae for calculating the entrainments observed in the outside air intake and in the indoor spaces:

Outside Air Inlet Entrainment

$$\text{Entrainment (\%)} = \frac{(C(inlet) - C(OA)) * 1E-9 * Q_v * 28.32 * 100}{Q_T} \quad (1)$$

where

$C(inlet)$ = the average tracer concentration in the outside air inlet (ppb)

$C(OA)$ = the average tracer concentration in the outside air (ppb)

Q_v = the flow rate of outside air through the inlet duct (cfm)

Q_T = the flow rate of pure tracer gas into the pollution source (lpm)

Area Entrainments

$$\text{Entrainment (\%)} = \frac{\dfrac{(C(t) - C(OA)) * 1E-9 * (Q_v/v) * 28.32 * 100}{(1 - e-(Q_v * t)/v)}}{Q_T} \quad (2)$$

where

$C(t)$ = the indoor tracer concentration in the building zone at time, t, (min)

$C(OA)$ = the average tracer concentration in the outside air (ppb)

Q_v = the flow rate of outside air into the building zone (cfm)

t = time since tracer injection (min)

V = the net indoor air volume (ft^3)

Q_T = the flow rate of pure tracer gas into the pollution source (lpm)

FUME ENTRAINMENT RESULTS

We measured the outdoor concentration of carbon monoxide (CO) using an electro-chemical analyzer to range from 3 ppm to 50 ppm. We noted the highest CO concentrations (e.g., 20 to 50 ppm) during periods when there were visible emissions of train exhaust from the sidewalk grates, in particular when trains were preparing to leave from the underground station. We continuously monitored the indoor concentrations of CO in the first-floor area using another electro-chemical analyzer. The indoor concentrations steadily increased from 7 ppm to 14 ppm during the 2.5-hour measurement period. We measured nitrogen oxide (NO) and nitrogen dioxide (NO_2) using a sorbent tube sampler which we analyzed using gas chromatography (e.g., P&CAM 231). We collected air samples from 16:15 to 18:30 during a weekday evening commute period. We observed outdoor concentrations of 0.64 ppm and 0.65 ppm for NO and NO_2, respectively. We simultaneously observed indoor concentrations ranging from 0.04 ppm to 0.48 ppm for NO and 0.05 ppm to 0.25 ppm for NO2.

The results of the tracer gas measurements are summa-

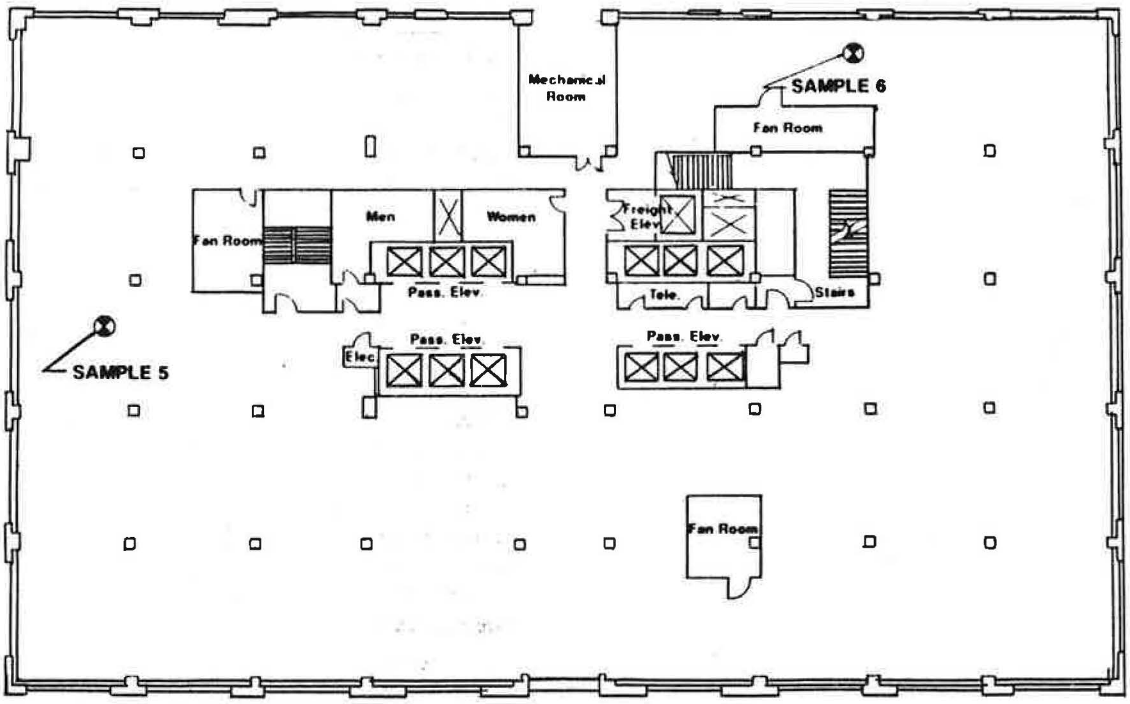

Figure 3 Floor plan of the second floor depicting the locations of the sampling points

TABLE 1

Tracer Gas Data Collected During Fume Entrainment Tests

Sample ID	Location	Time	Air Concentration (ppb)
X1	OA street	13:10	0.11
X2	OA inlet	13:07	0.11
X3	First floor south west	13:08	0.13
X4	First floor door	13:05	0.13
X5	Second floor west	13:05	0.13
X6	Second floor east	13:07	0.12
Tracer gas injection: 13:25–14:25			
A1	OA street	13:40	20.64
A2	OA inlet	13:41	113.42
A3	First floor south west	13:40	6.80
A4	First floor door	13:41	4.51
A5	Second floor west	13:41	2.38
A6	Second floor east	13:40	0.29
B1	OA street	13:55	5.37
B2	OA inlet	13.57	131.21
B3	First floor south west	13.55	13.20
B4	First floor door	13.56	10.54
B5	Second floor west	13.55	6.95
B6	Second floor east	13.56	1.31
C1	OA street	14:10	264.56
C2	OA inlet	14:11	29.00
C3	First floor south west	14:10	22.14
C4	First floor door	14:11	18.04
C5	Second floor west	14:10	6.95
C6	Second floor east	14:11	1.63
D1	OA street	14:25	8.74
D2	OA inlet	14:26	20.64
D3	First floor south west	14:25	25.51
D4	First floor door	14:26	21.76
D5	Second floor west	14:26	8.67
D6	Second floor east	14:26	1.26
E1	Mechanical Room	14:25	29.47
E2	AC-1 OA Duct-Bag	13:30–14:25	35.93

Spurce: Indoor Environmental Engineering, May, 1988

TABLE 2

Tracer Gas Data Collected During Fume Entrainment Test 2

Sample ID	Location	Time	Air Concentration (ppb)
N1	OA street	16:51	0.58
N2	OA inlet	16:52	0.48
N3	First floor south west	16:50	0.62
N4	First floor door	16:50	0.77
N5	Second floor west	16:48	0.13
N6	Second floor east	16:46	0.11
Tracer gas injection: 16:57–18:07			
O1	OA street	17:17	8:31
O2	OA inlet	17:18	7:34
O3	First floor south west	17:20	8.78
O4	First floor door	17:19	4.97
O5	Second floor west	17:15	4.97
O6	Second floor east	17:17	0.36
P1	OA street	17:31	27.96
P2	OA inlet	17:30	9.46
P3	First floor south west	17:34	9.67
P4	First floor door	17:33	8.50
P5	Second floor west	17:30	4.93
P6	Second floor east	17:31	3.07
Q1	OA street	17:47	3.11
Q2	OA inlet	17:48	14.84
Q3	First floor south west	17:51	11.77
Q4	First floor door	17:50	11.03
Q5	Second floor west	17:47	7.05
Q6	Second floor east	17:48	0.50
R1	OA street	18:07	1.49
R2	OA inlet	18:04	69.19
R3	First floor south west	18:07	14.42
R4	First floor door	18:07	15.09
R5	Second floor west	18:10	10.93
R6	Second floor east	18:11	0.83
S1	AC-1 SA	18:05	17.08
S2	AC-1 SA	18:06	17.49
S7	AC-1 OA Duct-Bag	17:15–18:10	24.57

Source: Indoor Environmental Engineering, May, 1988

rized in Tables 1 and 2. These air concentrations are also depicted in the concentration vs. time plots presented in Figures 4-7. The results of the entrainment calculations are presented in Table 3. We calculated the outside air inlet entrainment percentage as the ratio of the measured flux of tracer gas entering the outside air inlet to the measured flux of tracer released into the sidewalk exhaust grates. We computed the outside air flux from the measured outside airflow rate of 310 cfm and the average tracer gas concentrations measured in the outside air duct. We calculated the three building zone entrainments as the ratio of the computed flux of tracer gas entering each building zone to the measured flux of tracer released into the sidewalk exhaust grates. We computed the flux of tracer entering each building zone from the measured indoor tracer gas concentrations, the estimated indoor air space volumes, and assuming an effective building air exchange rate of one air change per hour in each of the three building zones. We calculated the total building entrainment as the sum of the three computed zone entrainment rates (i.e., first floor southwest, second floor east, and second floor west).

We computed the total entrainment of the diesel emissions from the sidewalk exhaust grates into the building to be 5.8% for Test 1 and 4.5% for Test 2. The majority of the entrained diesel emissions were traced to the the first-floor area, where 4.2% and 2.6% of the released tracer gas were observed for Tests 1 and 2, respectively. The average entrainment of diesel emissions into the building through the outside air inlet was measured to be 0.6% and 0.4%, respectively.

DISCUSSION AND RECOMMENDATIONS

We used a tracer gas technique to determine the total entrainment of diesel exhaust emissions from sidewalk grates to be 5.8% and 4.5% for a pair of consecutive tests. This represents a substantial amount of entrainment and is consistent with the proximity of the sidewalk exhaust grates to the building. Most of the entrained tracer gas was observed to enter the first-floor office area. The amount of entrainment occurring through the outside air inlet was computed to be just 0.6% and 0.4% of the total observed entrainment. Other potential sources of entrainment of diesel emissions from the sidewalk exhaust grates are:

1) Air leakage through the doors.
2) Air leakage through the building expansion joint.
3) Air leakage in the return air ducts of the mechanical room located on the mezzanine level.

We observed that the tracer concentration in the mezzanine mechanical room at the end of Test 1 was significant

TABLE 3

Sidewalk Diesel Emission Entrainment Tracer Gas Test Results

		Sidewalk Exhaust Fume Entrainment (%)[a]				
Test	Injection Time	Outside Air Duct	1st Floor	2nd Floor-W	2nd Floor-E	Total
1	13:25–14:25	0.6	4.2	1.4	0.2	5.8
2	16:57–18:07	0.4	2.6	1.8	0.1	4.5

a.) The outside air inlet entrainment percentage is calculated as the ratio of the measured flux of tracer gas entering the outside air inlet ot the measured flux of tracer released into the sidewalk exhaust grates. The outside air flux was computed from the measured outside air flow rate of 310 cfm and the average tracer gas concentrations measured in the outside air duct.

The building zone entrainments are calculated as the ratio of the computed flux of tracer gas entering the building zone to the measured flux of tracer released into the sidewalk exhaust grates. The flux of tracer entering each building zone was computed from the measured indoor tracer gas concentrations, the estimated indoor air space volumes, and assuming an effective building air exchange rate of one air change per hour in each of the three building zones.

The total building entrainment was computed as the sum of the three computed zone entrainment rates (i.e. 1st Floor + 2nd Floor West + 2nd Floor East).

Source: Indoor Environmental Engineering, May, 1988

and thus any leakage in the return air duct system would be a significant source of diesel emissions into the building.

The recommended mitigation for this type of fume entrainment is elimination of the source. In this case, eliminating the source may be as simple as sealing off the sidewalk exhaust grates and providing an alternate means of safely exhausting diesel emissions from the train station. Another option available should elimination of the source not be feasible is building pressurization with an air scrubber designed to remove the diesel emissions from the outside air.

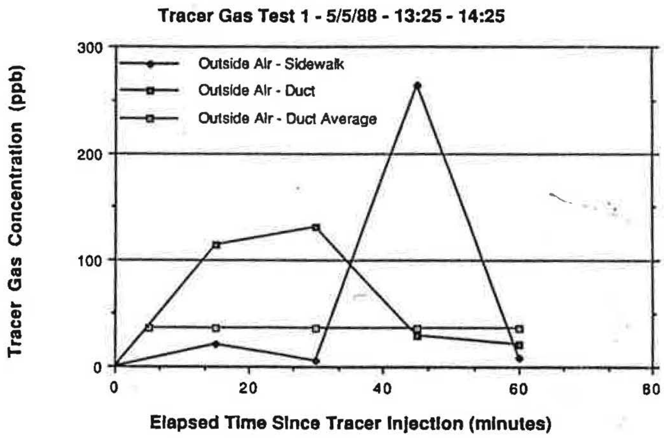

Figure 4 *Tracer gas outdoor concentrations during fume entrainment Test 1*

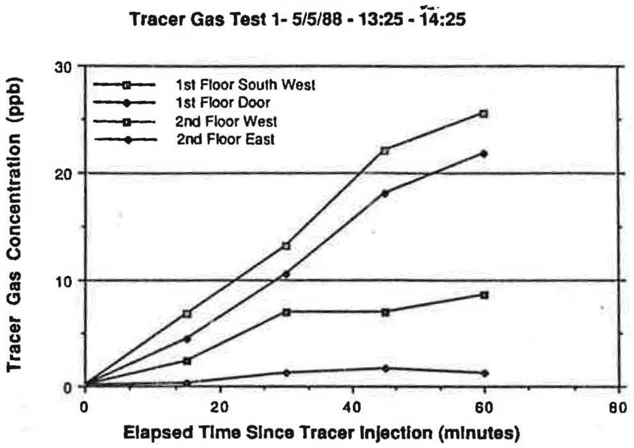

Figure 5 *Tracer gas indoor concentrations during fume entrainment Test 1*

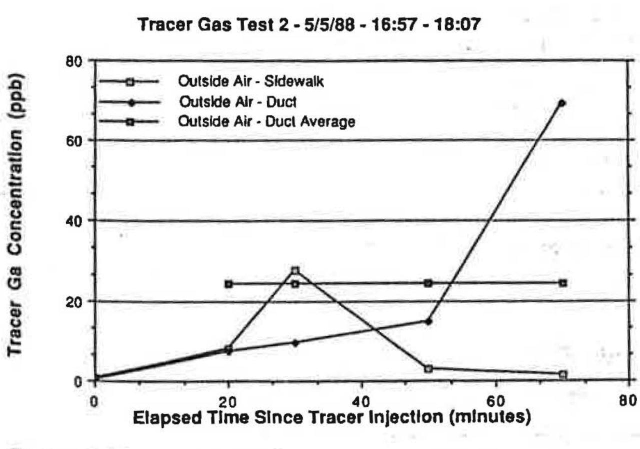

Figure 6 *Tracer gas outdoor concentrations during fume entrainment Test 2*

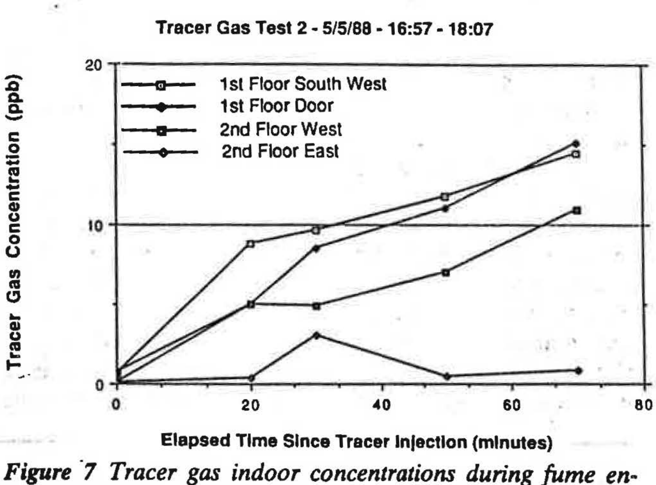

Figure 7 *Tracer gas indoor concentrations during fume entrainment Test 2*