REENTRY OF RADON FROM MITIGATION SYSTEM OUTLETS

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ABSTRACT

Some radon mitigation systems draw air with a high radon concentration from under the basement floors of houses and exhaust it outdoors. The objective of this project was to measure the reentry rates of radon released at roof level and at ground level near a house to determine whether exhaust above the roof is necessary. This was done by using a portable mockup of a radon mitigation system exhaust, with sulfur hexafluoride (SF_6) as a tracer gas.

The roof-level exhaust produced maximum indoor sulfur hexafluoride concentrations that were significantly lower than those from the ground-level exhaust. This suggests that the better radon discharge location is on the roof of a house.

INTRODUCTION

Background

Radon is an invisible, colorless, tasteless, odorless radioactive gas that occurs in nature. It is produced by radioactive decay of radium and can be found in rocks (granite and shale) and soils (phosphate and pitchblende) containing elements of the uranium decay series. Radon gas builds up in the air contained in soil and can escape from the soil into a house. Radon can enter a home through dirt floors, cracks in a concrete floor or walls, floor drains, joints, sumps, and the like due to air pressure differentials.

In cool weather, the density of the air in a house will be less than that outdoors so that the indoor pressure will be positive in the top part of the house and negative in the bottom part when the wind is low. Higher winds can also depressurize a house relative to the soil. Due to these pressure differentials, outdoor air will be drawn into the lower part of a house so that radon will tend to infiltrate into a building below grade. Contrary to early expectations, it has been found that indoor radon concentrations do not correlate well with house ventilation rates (EPA 1988).

The flow of air around buildings is a complex phenomenon. A detailed discussion of it is beyond the scope of this paper. Interested readers are referred to ASHRAE (1993a).

Purpose of Study

From 1985 to 1987, 40 houses in Pennsylvania received EPA-sponsored indoor radon mitigation systems (Scott et al. 1988; EPA 1992). These houses had high radon levels prior to the installation of the mitigation systems. When these houses were revisited in 1989-90, a significant percentage of them still had radon levels higher than the EPA's guidelines of 4 pCi/L (picoCuries per liter) (150 Bq/m^3).

The EPA sponsored a study (Henschel and Scott 1991) to determine the cause of these elevated indoor radon levels. It was discovered that in houses having active soil depressurization (ASD) systems, the primary cause of the elevated residual levels appeared to be re-entrainment of the high radon concentration in the exhaust from the basement subslab region. However, it was difficult to ascertain that indoor radon levels were caused by re-entrainment as opposed to infiltration from the basement subslab region or dispersion from high-radon water, and no conclusion could be reached.

The purpose of the present study was to determine the potential for radon to be re-entrained into a house when exhausted at different locations, configurations, and airflows. This was done by releasing SF_6 as a tracer gas by means similar to the release of radon from mitigation systems and measuring its concentration indoors and around the house.

PROJECT DESCRIPTION

Test House

The house that was tested is located in State College, Pennsylvania. It is a Cape Cod-style, two-story wood-frame house built in 1949. The basement walls are concrete block and the floor is poured concrete. There is a crawlspace under part of the house that is vented to the outdoors and to the basement. The house has wooden doors, wooden storm doors, double-hung windows, and wood-frame storm windows. House dimensions are 30 ft by 27 ft (9.8 m by 8.8 m). The garage is detached.

Procedure

Sulfur hexafluoride (SF_6) at a concentration of 1.0 part per million (ppm) was discharged vertically at the roof

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eaves of the house or horizontally away from the house at ground level. Measurements of SF_6 concentration were made by drawing air from each sampling point through a flexible tube to a switchable manifold that allowed each sampling point to be selected in turn. Each sample was drawn by a vacuum pump through a gas chromatograph, where the SF_6 concentration was measured, and was then discharged within the garage.

Equipment

The equipment used in this project consisted of the following five systems a SF_6 injection system, a SF_6 sampling and detection system, a N_2 carrier gas system, a smoke injection system, and a fan system and discharge outlet station.

The SF_6 injection system consisted of a cylinder of 10,000-ppm SF_6, a two-stage gas-regulating valve, 1/8 in. (3.2 mm) outer diameter (OD) nylon tubing, a flow-metering valve, a soap bubble flowmeter, and a brass SF_6 injection wand that was located in the discharge outlet of the active soil depressurization (ASD) system simulator. SF_6 flowed through the nylon tubing into the bubble flowmeter, where SF_6 flow was measured and set to a controlled rate by the metering valve to obtain a discharge outlet concentration of 1.0 ppm at 25 and 125 cfm (.71 and 3.54 m^3/min). The SF_6 passed through the injection wand to mix with air from the fan system and disperse in the outdoor air. The discharge outlet SF_6 concentration of 1.0 ppm was obtained by combining air containing 10,000 ppm of SF_6 with a flow rate of 70 mL/min (.0089 cfm) with pure air flowing at 25 cfm (.71 m^3/min). The SF_6 supply was proportionally higher when the airflow rate was 125 cfm (3.54 m^3/min). The SF_6 flow rate was measured with a 500-mL bubble flowmeter.

The SF_6 sampling system consisted of individual 100-ft (32.8-m) lengths of 1/4 in. (6.3 mm) OD polyethylene tubing mounted at the sampling sites. Air samples were drawn to the gas chromatograph through the polyethylene tubing, through a six-port rotary selector switch, and into the gas chromatograph by an auxiliary 1/30-hp (24.8-W), 12-in. (30.4-cm) Hg vacuum pump on the chromatograph outlet. The auxiliary pump was required because the existing sampling pump within the gas chromatograph is only capable of drawing air samples through a 6-ft (2.0-m) length of tubing. The SF_6 was detected with a commercially available gas chromatograph with an electron capture detector designed for SF_6 gas concentrations in the range from 10,000 parts per trillion (ppt) down to 10 ppt. Output voltages proportional to gas concentrations were digitally displayed on the SF_6 chromatograph panel (see Figure 1 for a sampling system schematic).

A sampling syringe was used to take readings of SF_6 concentration to verify results obtained through the tubing network and to conduct the outdoor dispersion testing. It was also used when SF_6 concentrations were found to be too high for the instrument to measure directly; therefore, sample gas dilution with pure air was necessary to decrease the concentration into the detection range. The contents of the syringe were injected into the gas chromatograph to obtain the SF_6 concentrations of the syringe samples.

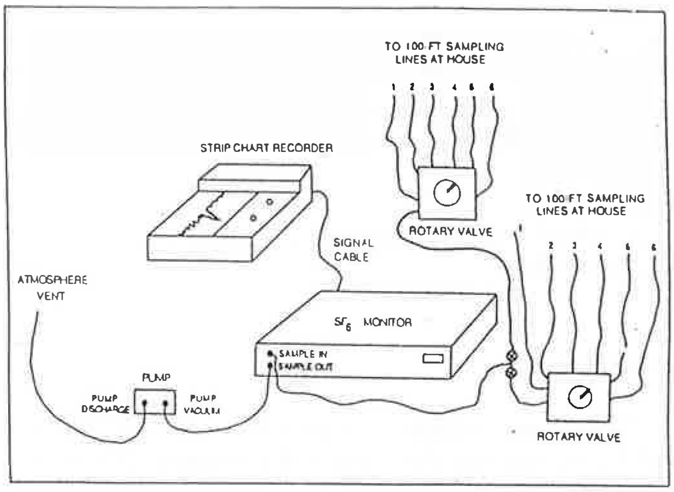

Figure 1 *Sampling system schematic.*

The SF_6 chromatograph requires oxygen-free (less than 0.5 ppm) nitrogen as a carrier gas. Polyethylene tubing transports the nitrogen to the chromatograph. Nitrogen passes through an oxygen purifier to ensure complete oxygen removal. A metering valve is used to adjust the flow to the required 0.1 standard ft^3/h (47.2 L/min) on the chromatograph flowmeter.

The SF_6 gas chromatograph was sited in a 6 ft by 6 ft (2 m by 2 m) thermostatically controlled, electrically heated test chamber constructed with 1-in. insulating board and located inside the garage.

To determine flow patterns and to assist in planning the SF_6 testing, smoke dispersion from the discharge outlet was observed and videotaped. The smoke injection system consisted of an electric smoke generator, smoke fluid, a duct adapter, and a ducting hose. The smoke fluid was electrically heated within the smoke generator to provide up to 120 m^3/min (≈ 4,400 cfm) of smoke. The smoke was injected into a "Y" fitting at the fan intake, resulting in smoke discharge at the fan outlet.

The fan system consisted of a 6 in. (15.2 cm) diameter centrifugal in-line duct fan, a motor-speed controller, a polyvinyl chloride (PVC) "Y" fitting, a flow measurement station, and a 50-ft (16.4-m) length of 6 in. (15.2 cm) diameter flexible intake duct so that intake air is drawn remotely from SF_6 release. This fan system was mounted on a hand truck for on-site mobility. The discharge outlet station consisted of a 4 in. (10.2 cm) diameter section of PVC pipe. The outlet station was directly attached to the fan system for grade-level testing of SF_6 dispersion or remotely located on the roof using a section of 4 in. (10.2 cm) diameter flexible duct. The SF_6 discharge concentration was set at 1.0 ppm for all testing. A fan system sketch depicting the discharge at 2.5 ft (.82 m) above grade level is shown in Figure 2.

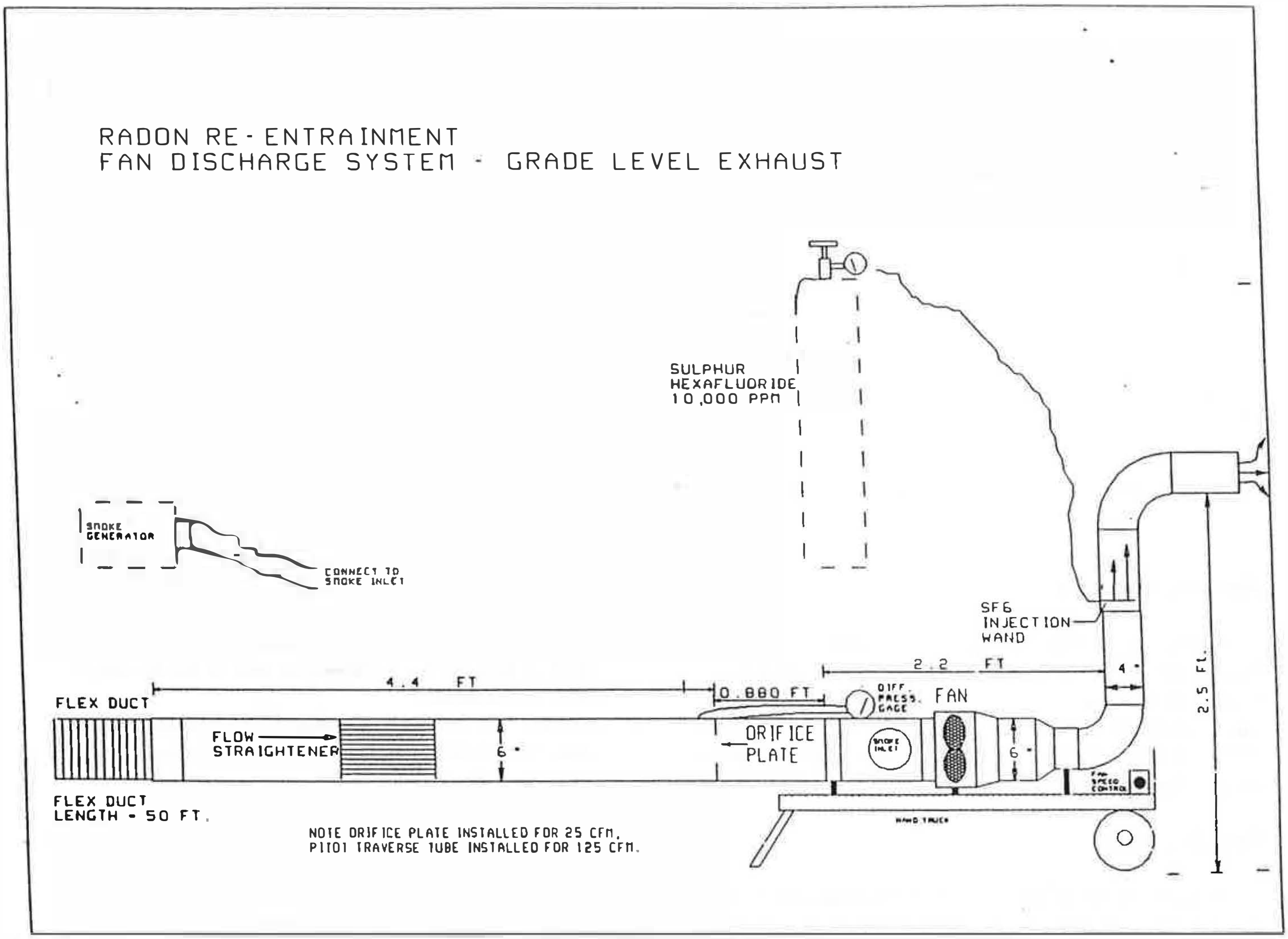

Figure 2 *Fan discharge system schematic.*

Weather conditions at the test site were monitored during each test with a portable weather station that measured wind velocity, wind direction, and air temperature. These climatic conditions were recorded manually at fixed intervals.

Discharge Outlet Locations

Releases of air containing SF_6 occurred both at grade level and above the roof eave. Grade-level exhaust was alternated between four locations at grade level—one at each side of the house. The horizontal exhaust configuration is shown in Figure 2. The above-eave vertical exhaust occurred 2 ft (.65 m) above the roof eave.

Sampling Sites

For the roof-level discharge outlet, the outdoor SF_6 sampling took place at nine sampling locations—eight stations on the house exterior walls (two levels per wall) and a sampling station located approximately 80 ft (26.2 m) away from the house. Grade-level discharge sampling was the same as described above, with the addition of exhaust dispersion testing at 12 sampling locations in a matrix surrounding each discharge outlet station, as shown in Figure 3. Samples were taken 5 and 15 ft (1.64 and 4.92 m) from the discharge outlet at heights of 2 and 5 ft (.65 and 1.64 m). Samples were taken with a 100-mL syringe.

Interior sampling took place at three sampling stations within the house—one sampling station for each floor level. Sampling stations were located in the central part of the house at 5 ft (1.64 m) above the floor. During testing, all interior doors were open except the basement door. Interior kitchen and bathroom fans were off. There was no forced mixing within the house.

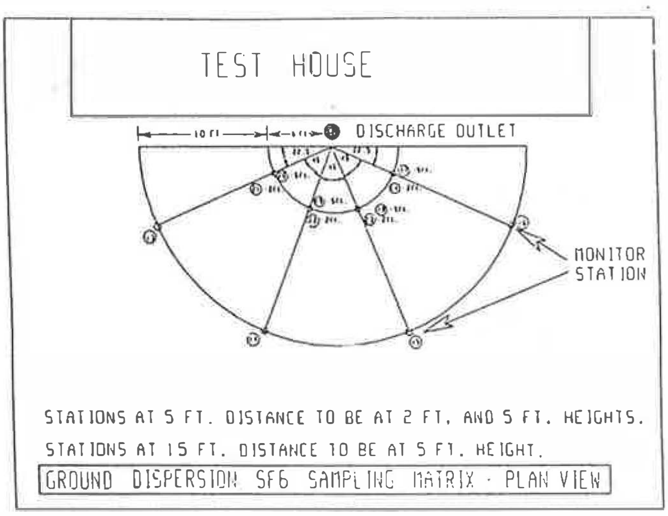

Figure 3 *Dispersion testing schematic.*

Blower Door Tests

Blower door testing indicated an average effective leakage area of 119 in.^{2} (768 cm^2). The annual average air infiltration rate was 0.55 air changes per hour (ach) (estimated using the method of *ASHRAE Standard 136-1993* ASHRAE 1993b]). The blower door tests were conducted with the furnace flue open and the wood stove flue closed.

Test Sequence

Prior to daily SF_6 release, baseline testing was done to find the SF_6 concentration in the ambient air or within the house as a check for residual SF_6 from previous testing. This test always yielded zero concentration of SF_6 in the air.

Daily testing consisted of three full cycles of testing at each specific test condition. Each cycle included two readings from each of the sampling stations. If indoor SF_6 levels had not reached steady state, indoor readings continued if possible until steady SF_6 levels were attained in the test house.

SF_6 release testing was conducted for exhaust airflows of 25 and 125 cfm (.71 and 3.54 m^3/min), four wind directions, low and high wind velocities, different discharge outlet locations, and different outlet configurations. Twenty-one one-, two-, or three-day tests were performed.

Often, at the anticipated completion of the testing cycle, the indoor SF_6 concentration was still changing. To ensure that the indoor SF_6 level reached steady state, testing was extended, with SF_6 release continuing through the night. In all cases, the SF_6 steady-state concentration was reached by the second day of testing, although one test was continued for three days.

On June 30, 1993, the whole-house exhaust fan was operated during testing. This procedure resulted in the indoor SF_6 level reaching steady-state concentration within a few hours, in contrast to the other tests, in which the steady state did not usually appear to have been reached during one 8- to 12-hour test period.

RESULTS

Interior SF_6 Concentrations

Following the initiation of a release of SF_6 at the discharge outlet, the indoor SF_6 concentration gradually increased during the test day. During the two- and three-day tests, the concentration was steady by the beginning of the second day of continuous testing. The consecutive indoor readings were relatively consistent, unlike the outdoor readings.

Tables 1 and 2 list the peak and steady-state SF_6 concentrations, respectively, for each test day. Observations based on the test results include the following:

- The highest indoor SF_6 concentration for all the testing occurred in the basement, at 2,200 ppt. This is 0.22% of the 1.0-ppm discharge outlet concentration. For ground-level testing, indoor SF_6 concentrations tend to stabilize near 0.1% (1,000 ppt) or less of the discharge outlet concentration.
- Usually, the indoor concentrations were higher for ground-level discharge than for rooftop discharge. This would be expected, due to the negative pressure condition of the house at the lower levels near the ground-level discharge outlet.
- During ground-level discharge, the highest indoor SF_6 concentrations tended to be on the first floor. No pattern was apparent for rooftop release.
- There was no noticeable difference in indoor SF_6 concentrations that could definitely be attributed to a discharge outlet airflow of 25 or 125 cfm (708 or 3,540 mL/min), even though five times more SF_6 is released at 125 cfm (3,540 mL/min) than at 25 cfm (708 mL/min).
- The very low steady-state concentrations were all on days of rooftop discharge.

Exterior SF_6 Concentrations

Exterior Walls SF_6 gas sampling often resulted in large variations in concentration for consecutive readings at each sampling site, at the same sampling site throughout the day, and from one sampling site to another. Table 3 lists the peak outdoor SF_6 concentrations for each test day. Distinct SF_6 build-up patterns were noted as follows:

(a) The outdoor concentration was highly dependent on wind conditions.

(b) In most cases, the peak SF_6 concentration on the walls was much lower for roof discharge than for ground-level discharge.

TABLE 1
Daily Peak Indoor SF_6 Concentration

Test Date	Discharge Location	Outlet Airflow cfm (m^3/min)	House Level	Peak SF_6 Level (PPT)
11/17/92	roof	25 (0.71)	second	83
11/19/92	ground	25 "	basement	364
11/20/92	ground	125 (3.54)	basement	2261
5/3/93	roof	125 "	basement	30
5/4/93	roof	25 (0.71)	basement	10
5/14/93	roof	125 (3.54)	second	1404
5/19/93	roof	125 "	first	557
5/20/93	roof	25 (0.71)	second	65
5/21/93	ground	25 "	first	883
5/22/93	ground	25 "	second	1128
5/24/93	ground	125 (3.54)	first	806
5/25/93	ground	125 "	basement	1658
5/26/93	ground	125 "	first	1400
5/27/93	ground	125 "	first	998
6/2/93	ground	125 "	basement	900
6/3/93	ground	125 "	first	815
6/4/93	ground	125 "	first	833
6/7/93	ground	25 (0.71)	first	425
6/8/93	ground	25 "	second	1739
6/9/93	ground	25 "	second	761
6/30/93	ground	25 "	first	801

(c) The highest recorded SF_6 concentration on the house wall was 16,654 ppt, or 1.6% of the release concentration. This reading was 56% higher than the next highest reading of 10,636 ppt.

(d) Except for as noted in (c) above, all SF_6 concentrations on the house wall were less than 1.0% of the 1.0-ppm discharge outlet concentration.

(e) For ground-level testing, the highest SF_6 concentrations were at the walls adjacent to the SF_6 discharge outlet (12 out of 14 tests).

(f) For ground-level testing, the highest peak SF_6 concentrations were at a discharge airflow of 125 cfm (3.54 m^3/min).

Dispersion Ground dispersion samples were taken to determine the SF_6 concentration away from the house around the outlet. Table 4 lists peak dispersion SF_6 levels for each test day. The following observations were made from these results:

- The SF_6 concentrations at locations away from the walls but near the outlet reached higher values than at the test house walls.
- Peak concentrations per test day ranged from 8,365 ppt to 15,651 ppt. The exception was on June 8, 1993, when the peak SF_6 concentration was only 173 ppt.
- The air samples yielded a wide range of SF_6 levels each day, from zero at some sampling stations up to very high levels.
- At a discharge outlet airflow of 25 cfm (.71 m^3/min), the peak concentrations were measured 2 ft (.65 m) above the ground. At an airflow of 125 cfm (3.54 m^3/min), the peak concentrations were at the 5-ft (1.64-m) height at stations located 5 ft (1.64 m) from the discharge outlet.

Ground-Level vs. Rooftop Discharge

These observations regarding the impact of the discharge outlet location on the test results were based on all the results obtained, rather than on individual comparisons of pairs of similar test days. However, during tests conducted on May 20 (rooftop) and May 21 and 22 (ground level), weather conditions were similar and the discharge airflow was at the same rate. Hence, the different SF_6 concentrations at the test site could be attributed to the discharge outlet location.

On May 20, 1993, with roof discharge, the indoor SF_6 concentration reached 50 to 60 ppt. On May 21, 1993, with ground-level discharge, indoor levels stabilized at 300 to 900 ppt, eventually reaching the 500- to 1,000-ppt level on May 22, 1993 (continuous testing). The indoor SF_6 levels were 10 times higher within the house for ground-level discharge than for rooftop discharge. The ground-level release also resulted in higher outdoor SF_6 levels than the rooftop release. On May 20, only 5 outdoor air samples were higher

TABLE 2
Indoor Steady-State SF_6 Concentrations

Test Date	Outlet Airflow cfm (m^3/min)	House Level	Number of Samples	Average SF_6 Level (ppt)
1/19/92	25 (0.71) G*	basement	4	349
11/19/92	25 " G	first	4	317
11/19/92	25 " G	second	4	296
11/20/92	125 (3.54) G	basement	5	2195
11/20/92	125 " G	first	4	1708
11/20/92	125 " G	second	4	1643
5/3/93	125 " R	basement	6	25
5/3/93	125 " R	first	6	10
5/3/93	125 " R	second	6	15
5/4/93	25 (0.71) R	basement	6	4
5/4/93	25 " R	first	6	3
5/4/93	25 " R	second	6	0
5/22/93	25 " G	basement	4	660
5/22/93	25 " G	first	5	906
5/22/93	25 " G	second	4	1053
5/24-25/93	125 " G	basement	6	1233
5/24-25/93	125 " G	first	6	1125
5/24-25/93	125 " G	second	6	1074
5/26/93	125 (3.54) G	basement	4	651
5/26/93	125 " G	first	4	1137
5/26/93	125 " G	second	4	627
6/2-4/93	125 " G	basement	14	484
6/2-4/93	125 " G	first	14	671
6/2-4/93	125 " G	second	14	611
6/8-9/93	25 (0.71) G	basement	12	515
6/8-9/93	25 " G	first	15	682
6/8-9/93	25 " G	second	12	859
6/30/93	25 " G	basement	6	231
6/30/93	25 " G	first	14	368
6/30/93	25 " G	second	13	314

*Discharge outlet location (G - ground level; R - rooftop).

than 200 ppt whereas on May 21, 18 samples were higher than 200 ppt. The May 20 average outdoor SF_6 level was 79.3 ppt, while the May 21 average outdoor level was 197.4 ppt.

DISCUSSION

As testing was limited and daily testing contained many variables, it is difficult to describe a result as being due to a specific condition. This is due to the continuous change in weather conditions, an uncontrolled variable and the dominating factor.

For example, for one discharge location, a discharge airflow reduction from 125 to 25 cfm (3.54 to .71 m^3/min) appeared to cause a decrease in indoor SF_6 concentrations (May 14, 1993 vs. May 4, 1993 and May 19, 1993 vs. May 20, 1993 tests). However, this could also be a result of different weather conditions on the test days.

A complicating factor in this project was the occupancy of the house. Although the occupant was a member of the study team and cooperated as fully as possible, this did put some limitations on the project. Other projects should use unoccupied houses if possible.

Exterior SF_6 Levels

The outdoor SF_6 concentrations fluctuated wildly from one reading to the next. The exception to this is at the upwind monitoring stations, as these tend to maintain a near-zero SF_6 level continuously. The large fluctuations in outdoor SF_6 levels downwind of the exhaust outlet correspond to the fluctuations in airflow patterns observed in the smoke releases.

TABLE 3
Daily Peak Outdoor SF_6 Concentrations on Face of House
(Monitor Stations 5 through 12)

Test Date	Discharge Location	Outlet Airflow cfm (m^3/min)	House Wall	Peak SF_6 Level (PPT)
11/17/92	roof	25 (0.71)	East U**	883
11/19/92	ground E*	25 "	East L	392
11/20/92	ground S	125 (3.54)	South L	9238
5/3/93	roof	125 "	North L	1983
5/4/93	roof	25 (0.71)	North U	333
5/14/93	roof	125 (3.54)	East L	883
5/19/93	roof	125 "	East L	883
5/20/93	roof	25 (0.71)	North L	883
5/21/93	ground N	25 "	North L	1890
5/24/93	ground N	125 (3.54)	East U	3272
5/25/93	ground N	125 "	North L	4450
5/26/93	ground N	125 "	North L	4446
5/27/93	ground N	125 "	North U	16654
6/2/93	ground W	125 "	West/North L	4450
6/3/93	ground W	125 "	West U	4450
6/4/93	ground W	125 "	West L	10636
6/7/93	ground W	25 (0.71)	North L	883
6/8/93	ground W	25 "	West L	3112
6/9/93	ground W	25 "	West U	2457
6/30/93	ground W	25 "	West U	2628

*Discharge outlet ground location on side of house (N - north, E - east, S - south, W - west).
**Level of house wall (L - lower, U - upper).

TABLE 4
Daily Peak Dispersion SF_6 Concentrations
(Monitor Stations 13 through 24)

Test Date	Outlet Airflow cfm (m^3/min)	Station Number	Sampling Distance ft (m)	Sample Height	Peak SF_6 Level (ppt)
6/2/93	125 (3.53)	18,19	5 (1.52)	5 (1.52)	15651
6/3/93	125 "	18	5 "	5 "	14675
6/4/93	125 "	18	5 "	5 "	13935
6/7/93	25 (0.71)	22	5 "	2 (0.61)	8365
6/8/93	25 "	21	5 "	2 "	173
6/9/93	25 "	23	5 "	2 "	14621

Notes:
1. Station number refers to the "Ground Dispersion SF_6 Sampling Matrix."
2. Distances are measured from the discharge outlet.
3. Heights are measured aboveground.
4. Discharge released horizontally 2.5 ft (.82 m) abovegrade.

Interior SF_6 Levels

Inside the house, SF_6 concentration increased within 15 minutes of outdoor SF_6 release. The interior readings were constant during each sampling cycle. The SF_6 concentration tended to increase steadily with time, then stabilize at a steady-state level. When SF_6 release was halted, the interior SF_6 concentration gradually declined to zero levels.

CONCLUSIONS

When SF_6 gas is released to the atmosphere through a grade-level or roof discharge outlet station, it can re-entrain into air entering the house, possibly reaching an indoor concentration of 0.1% or more of the exhaust SF_6 concentration. The outdoor concentration may reach levels of more than 1.0% of the exhaust SF_6 concentration.

The test results indicate that to minimize indoor radon levels, the better discharge location is the roof of the house, as this greatly reduces the indoor steady-state concentration.

Further testing is recommended to determine the impact of weather and site conditions on the test results. As only one house location was tested, the results of this study are site specific. Additional testing in houses at different locations is recommended to establish more generally applicable conclusions.

ACKNOWLEDGMENT

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