

Experimental Characterization of Ventilation Systems in Buildings

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■ Tracer experiments, involving sulfur hexafluoride, were used to obtain quantitative data regarding actual residence time distributions in rooms and hallways, and contamination caused by reentry of laboratory fume hood exhausts into a building. Application of a mixing factor, k , was found to be of use, and measured values ranged from 0.3 to 0.7 in small rooms without fans. One experiment involved a roof exhaust with ventilation intakes both on an adjoining roof and at ground level; in this experiment more of the exhaust reentered the ground level intake of the same building as compared to the roof intake of an adjoining building. In another experiment, 20% of the fumes exhausted were found to reenter the ventilation system.

The air quality of urban atmospheres is being widely discussed. In spite of the fact that a significant portion of a person's life is spent within buildings, the air quality within buildings has been relatively overlooked. Accurate characterization of airflow through buildings is important for both personal comfort and safety. Of major importance in various facilities is the length of time required for purging until the concentration of toxic species lowers to a safe level. Also of major concern is the degree of contamination caused by emissions from laboratory fume hood exhausts, which reenter the original building and surrounding buildings. In extreme cases, buildings have been evacuated because of the reentry of toxic exhaust fumes (Clarke, 1965).

Probably the most useful method of characterizing the effectiveness of room and hallway ventilation is the mixing factor guide reported by Constance (1970). If the room under consideration is ideally well-mixed, then following a spill of a pollutant, the concentration will decrease due to purging as indicated by the equation:

$$c = c_0 e^{-(Q/V)t} \quad (1)$$

Some time ago Lidwell and Lovelock (1946) noted that if the room is not well-mixed, then the rates of decay will not necessarily be logarithmic nor will the decay rates be the same in all parts of the room. Lidwell and Lovelock also noted that in practice it is usually possible to fit a curve of the type:

$$c = c_0 e^{-Kt} \quad (2)$$

where K is a constant. This idea is identical to that used by Constance in his use of the mixing factor k :

$$c = c_0 e^{-k(Q/V)t} \quad (3)$$

Values of k are normally estimated to be from $1/3$ to $1/10$. Using a tracer-gas technique, values of k can be experimentally measured and thus accurately characterize room ventilation.

A number of studies have considered airflow around buildings and the location of fume exhausts to minimize reentry. Almost all these studies have required the building of scale models and have used smoke or chemical tracers in controlled wind and water tunnel experiments. Fan and Brooks (1968) made water tunnel tests of a scale model of the west campus of the California Institute of Technology using a dye tracer; they showed that the intake vent of Crellin—a chemistry laboratory—is presently located in possibly the worst place for contamination by reentry of exhaust fumes. Evans (1957) made extensive wind tunnel tests with a smoke tracer on a larger number of building and roof shapes showing the eddy formation downwind. Halitsky (1962, 1963) used SO_2 as a tracer in wind tunnel studies of scale model buildings to determine the dilution factor from exhaust vents to intake vents. Halitsky (1965) and Fan and Brooks (1968) have also theoretically modeled plume behavior to estimate exhaust stack heights to limit contamination of building air intakes. Davis and Moore (1964) made wind tunnel tests using a smoke tracer on a scale model of a tall nuclear reactor building. They found that the transition from a steady plume to a turbulent wake depended on the ratio of the exhaust velocity to wind velocity. Clarke (1965) also commented on the significance of this ratio and the importance of having a large exhaust velocity. Munn and Cole (1967) released a fluorescent tracer, uranine dye, from an actual building exhaust stack and measured concentrations 500–1000 ft downwind. Likewise, Turk et al. (1968) released SF_6 , the tracer used in the present experiment, from an actual building stack and measured concentrations 650–1000 meters downwind.

To the authors' knowledge, no experimental tracer tests have been made to determine the effectiveness of ventilation in rooms and the contamination resulting from reentry of fume hood exhausts under real conditions. The goal of this investigation was to gain quantitative knowledge in these two areas. No legal standards exist for the design and location of fume hood exhausts. Thus, these measurements are vital for the safety of personnel working in any building which exhausts toxic fumes.

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Experimental

The analytical technique involved a gas tracer detected by electron capture gas chromatography. The electron capture detector was similar to that first developed by Lovelock and Lipsky (1960). Sulfur hexafluoride (SF_6) was used as the tracer gas. Lester and Greenberg (1950) have shown that SF_6 is completely nontoxic; rats were kept for 24 hr in an atmosphere of 80% SF_6 and suffered no ill effects. Previous studies (Collins et al., 1965; Clemons and Altshuler, 1966) have shown that SF_6 can be detected in concentrations of 1 part in 10^{11} using the technique of electron capture gas chromatography. Thus, since it is physiologically inert and easily detectable in low concentrations, sulfur hexafluoride is an excellent atmospheric tracer. Clemons et al. (1968) traced air movements over distances of 75 miles from a location where pure SF_6 was released at 1 lb/min for 1 hr.

The instrument used in this study was a portable electron capture gas chromatograph (Analytical Instrument Development, Inc., West Chester, Pa.) equipped with a 1-ml loop gas sampling valve. The detector contained a 200-mCi tritium foil which under operating conditions produced a standing current of 4×10^{-9} A. An 8 ft \times $\frac{1}{8}$ in. stainless steel column was packed with 80–100-mesh 5A Molecular Sieve. This column caused the SF_6 to elute first, followed by an oxygen peak; any water vapor was adsorbed by the Molecular Sieve. The carrier gas was prepurified nitrogen which was run at 120 ml/min. The column and detector were kept at 55°C. Integration of the SF_6 peak was accomplished by an Infotronics Model CRS-100 digital electronic integrator.

Due to the difficulty in making prepared standards with an SF_6 concentration of 10^{-11} , calibration was accomplished by means of a well-mixed exponential dilution system, similar to that used by Saltzman et al. (1966). A 6 \times 6 \times 6-in. Lucite cube was built with a magnetically driven propellor positioned inside. A slow airflow rate of 104 ml/min resulted in one air change every 33.5 min and thus assured good mixing. If the system were well-mixed, the dilution would follow that equation:

$$c = c_0 e^{-N} \quad (4)$$

where c_0 is the initial concentration and N is a number of air changes. A graph of peak area vs. number of air changes should thus yield a slope of -1 , as shown in Figure 1. Figure 2 shows the relationship between peak area and actual SF_6 concentration. The minimum detectable SF_6 concentration under the operating conditions was 3×10^{-12} . The detector has a linear dynamic range of approximately 10^8 below SF_6 concentrations of 2×10^{-9} . At higher concentrations, the detector becomes overloaded; however, a calibration curve is possible up to 1 ppm if standard operating conditions are maintained.

Air samples were taken by dry 250-ml polyethylene bottles using the technique reported by Collins et al. (1965). The sampling procedure was to squeeze the bottle hard 10 successive times, one squeeze a second. Field tests showed excellent reproducibility, and samples could be contained in the bottles for at least a period of two weeks. For analysis, a cap for the bottles was mounted on the inlet of the gas sampling valve of the chromatograph. A sample was analyzed by attaching the polyethylene bottle, squeezing the bottle and thus flushing at least 10 ml through the 1-ml sampling loop and injecting the sample before releasing the squeeze on the bottle. Although polyethylene bottles proved quite useful in sampling, surface adsorption of SF_6 was a problem. For example, if a bottle contained an SF_6 concentration of 10^{-7} ,

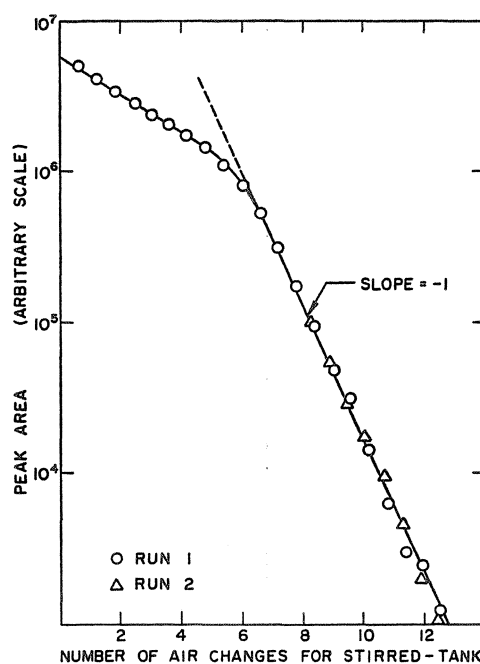


Figure 1. SF_6 peak area vs. number of air changes in the well-stirred dilution apparatus

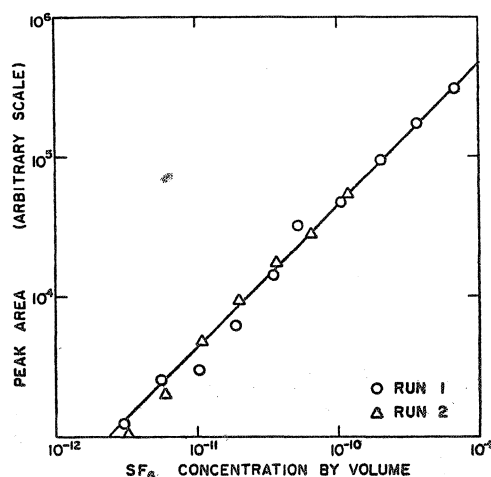


Figure 2. SF_6 calibration curve calculated from the exponential dilution

after cleaning by rapid flushing with pure air, desorption of SF_6 produced concentrations up to 5×10^{-10} , which limited reuse of the bottle.

Room and Hallway Ventilation Tests and Results

The first step was to test the theory for a well-mixed room. A small (16 \times 10 \times 9) rectangular room, Room 27, was chosen in the basement of Caltech's Spalding Laboratory. The basement and room have a simple in-out ventilation system with no recirculation. From measuring the volumetric flow rate, Q , at the intake vent of the room and the room volume, V , as shown in Table I, the theoretical characteristic

Table I. Theoretical Residence Times for Basement Rooms

Room	Q , ft ³ /min	V , ft ³	τ , min
25	384	1440	3.8
27	316	1440	4.6
31	328	1440	4.4

time, τ , for one air change can be calculated:

$$\tau = V/Q \quad (5)$$

For Room 27, $\tau = 4.6$ min.

Four large fans were placed strategically in the room to provide good mixing. One-tenth ml of pure SF_6 was injected in front of one of the fans, and air samples were taken every 2 min in the center of the room and in one corner of the room near the exhaust vent. The results are shown in Figure 3. The two locations in the room gave essentially identical results. The dotted line represents the best fit of a straight line through the data points. The negative reciprocal of the slope of this line gives the effective residence time, t_{exp} , for one air change (the time required for concentration to decrease by $1/e$). From the graph, $t_{\text{exp}} = 5.1$ min. The solid line indicates the theoretical well-mixed residence time, $\tau = 4.6$ min. The mixing factor as used by Constance (1970) can thus be defined:

$$k = \frac{\tau}{t_{\text{exp}}} \quad (6)$$

In this case, $k = 0.90$; thus, the fans produced almost complete well-mixing. Without the fans, the mixing factor can be much less, as will be shown below.

An important point is that the integrated concentration-time curve, multiplied by the flow rate Q , should equal (theoretically) the initial amount of tracer injected into the room:

$$Q \int_0^{\infty} c dt = v_0 \quad (7)$$

where v_0 is the initial volume of tracer. In this case, integration produced a total volume of 0.092 ml, quite close to the injected volume of 0.10 ml. Thus, essentially all the injected tracer was measured, and no erroneous readings were caused by previous contamination of the room.

A larger scale test was made to determine the efficiency of the ventilation system of the entire basement of Spalding Laboratory. The basement has one main intake vent which distributes fresh air to all the rooms. Air from the rooms is exhausted into the hallway, and one large vent exhausts the hallway air. There is no recirculation. Pertinent ventilation data are given in Table I for three of the rooms.

One liter of pure SF_6 was injected into the intake vent of the basement system, and SF_6 concentrations were sampled in the above three rooms and at both ends of the hallway. Rooms 25 and 27 were sampled at the center of the room and Room 31 was sampled 3 ft from one corner of the room. Figure 4 shows the results for these three rooms. Concentrations peaked very quickly in all three rooms. By coincidence, the data for Rooms 25 and 27 fell on the same straight line; thus, both rooms had essentially the same actual residence time. Calculations for the three rooms are summarized in Table II.

The mixing factors in the center of the room are quite high;

Table II. Experimental Residence Times and Mixing Factors for Basement Rooms

Room	Location	t_{exp} , min	k
25	Center of room	6.7	0.56
27	Center of room	6.7	0.68
31	Corner of room	14.6	0.30

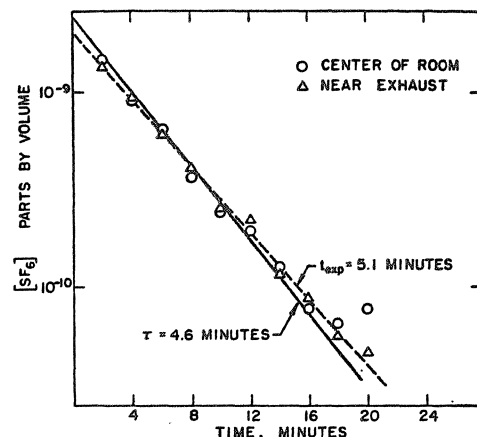


Figure 3. Results of the well-mixed ventilation test in Spalding, Room 27

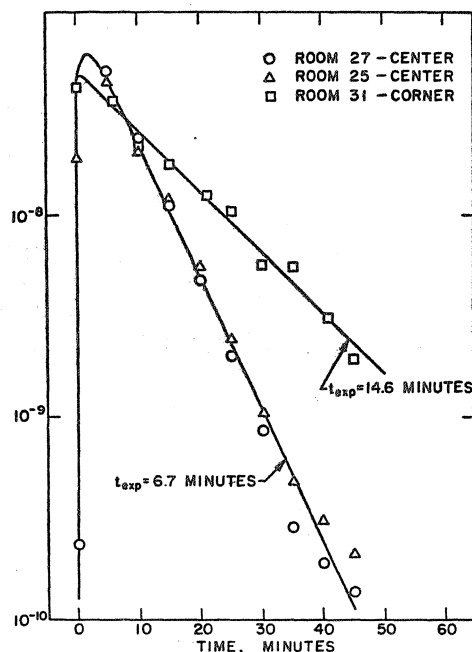


Figure 4. Results of the Spalding basement ventilation test for Rooms 25, 27, and 31

however, the corner of Room 31 had a mixing factor slightly less than $1/3$. Thus, the normal estimate of $k = 1/3$ to $1/10$ is reasonably valid. The rooms tested were rather small (16×10 ft) and larger rooms would presumably have worse mixing in corners and thus lower mixing factors.

Data from the two ends of the hallway are shown in Figure 5. Again, the concentrations peak rapidly. The break in slope of the curve for the west end of the hallway is difficult to explain since all rooms exhaust into the hallway and thus airflow is quite complicated. However, using the lower part of both curves, $t_{\text{exp}} = 18.0$ min for the east end and 22.8 min for the west end of the basement hallway. Thus, we can assume one complete air change takes place in the basement roughly every 30 min, to be on the safe side. If a sudden leak developed which flooded the basement with a 10^{-3} concentration of chlorine gas, the basement would have to be evacuated since the recommended safe threshold limit for chlorine gas is 1 ppm (Committee on Threshold Limit Values, 1962). Seven air changes would be needed to reach 1 ppm ($e^{-7} \cong 10^{-3}$) and thus, the time required for this dilution would be 7×30 min or 3.5 hr.

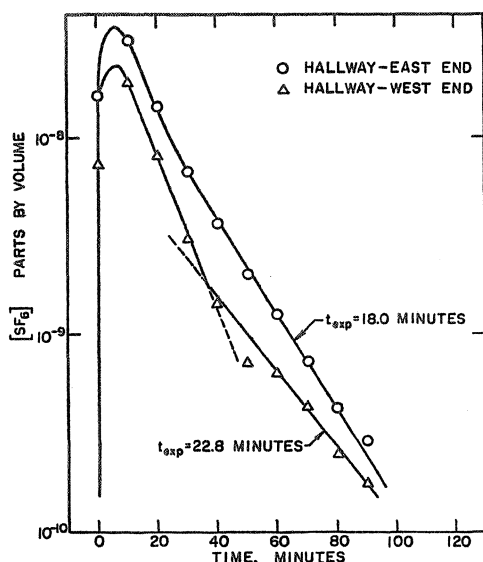


Figure 5. Results of the Spalding basement ventilation test for the east and west ends of the basement hallway

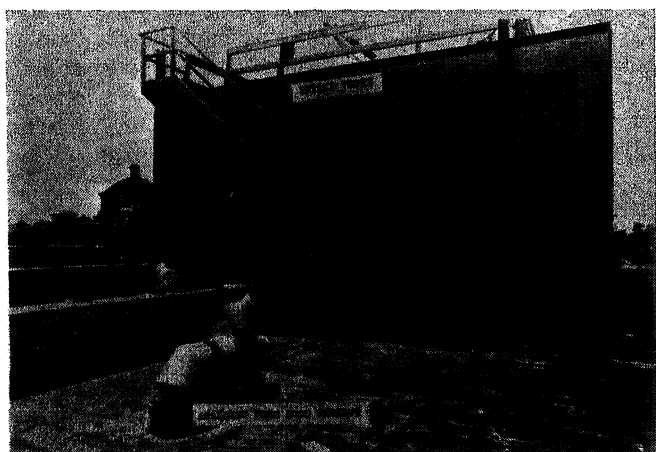


Figure 6. Roof of Spalding, showing the fume hood outlet from Room 236 and the main ventilation intakes

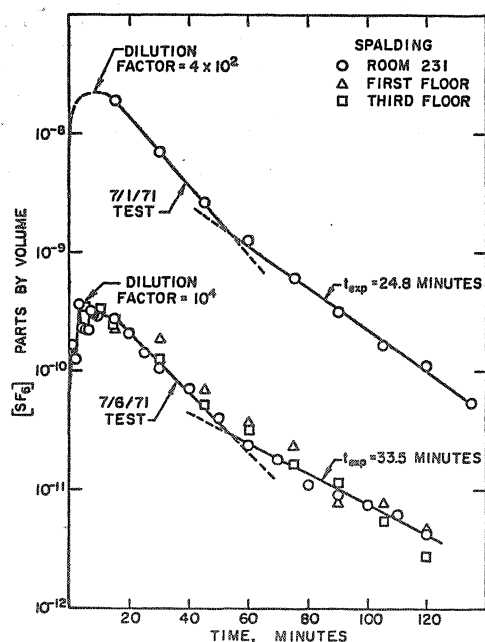


Figure 7. Results of two fume hood releases of SF_6 from Spalding, Room 236

Fume Hood Tests and Results

As mentioned previously, most studies concerning dilution of exhaust gases from buildings have used scale models in controlled wind and water tunnel experiments. In the present study, SF_6 was released inside a laboratory fume hood and the amount reentering the building after leaving the exhaust was measured in several locations inside the building.

Two tests were made from a fume hood in Room 236 in Spalding Laboratory; the room is a chemical engineering research laboratory. Spalding is a rather large, rectangular three-story building with the main ventilation intake and exhaust on the roof along with 10 fume hood exhausts. The roof ventilation system has some recycle and serves the first three floors; the basement has an independent ventilation system. Surprisingly, the fume hood exhaust for Spalding 236, shown in the foreground of Figure 6, was located only 16 ft from the main intake of the ventilation system (the three large panels in the background).

In the first test, pure SF_6 was released at a rate of 144 ml/min for 10 min into a fume hood which had a flow rate of 590 ft³/min. Therefore, the exhaust SF_6 concentration was 8.7×10^{-6} . Measurements of the amount of SF_6 which reentered the building were taken in Room 231 of Spalding; the door was kept closed to prevent any direct contamination from Room 236, the release point. Wind direction was not measured for this test.

Results are shown in the upper curve of Figure 7. Surprisingly high concentrations were reached in the building. A dilution factor, D , can be defined:

$$D = \frac{\text{Exhaust concn}}{\text{Max. concn recorded in building}} \quad (8)$$

For this case, $D = 400$. The minimum value of D , because of the large area of the intake vents, would occur if the entire fume exhaust reentered the intake vent. Since the flow rate of the intake vent is approximately 50,000 ft³/min and the fume hood exhaust is 590 ft³/min, the minimum dilution factor would be:

$$D_{\min} = \frac{50,000}{590} = 85 \quad (9)$$

Thus, in this case, 85/400 or about 20% of the exhaust fumes reentered the ventilation system. The intake vent in this case had such a large area (14 × 24 ft) it could easily accommodate the width of a plume from the exhaust duct even under very unstable conditions.

A second test from the same fume hood was made releasing pure SF_6 at a rate of 58 ml/min for 10 min. The exhaust concentration in this case was 3.5×10^{-6} . Measurements were made in 231 Spalding and also in the first and third floor hallways of Spalding. The wind direction was from the south, blowing in gusts in the same direction as the fume hood exhaust (Figure 6). Results are shown by the lower curve of Figure 7.

The dilution factor D (exhaust concn/max. concn inside) in this test was about 10^4 . Thus, wind conditions are extremely important in determining contamination: in this test, the wind blew most of the exhaust fumes away from the intake; in the first test, 20% of the fumes reentered (wind direction was not measured).

Samples taken on each of the three floors were almost identical, indicating that any exhaust fumes reentering the building were well-mixed after entering the intake vent. Both tests showed a break in the slope of the curves for the 231 Spalding

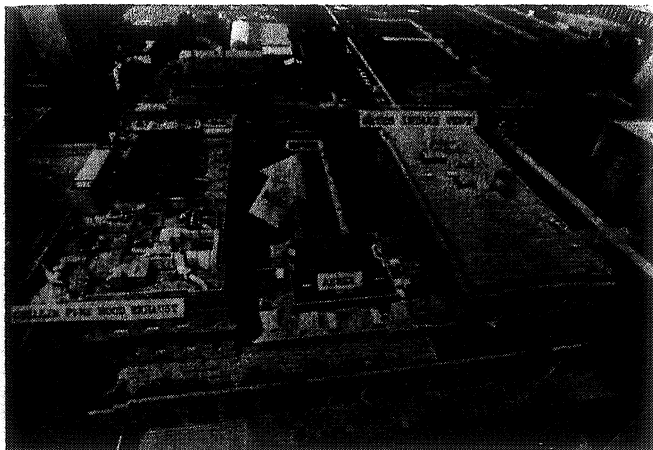


Figure 8. Overall view of Crellin (left), the annex, and Gates, showing the fume hood outlet from Crellin, Room 357 and the ventilation intake of Gates

data at about 50 min; this phenomena is probably due to small eddies in corners of the room. The experimental residence times, $t_{exp} = 24.8$ min and 33.5 min, are quite long, indicating that recirculation is not desirable in buildings with fume hood exhausts.

One additional fume hood release test was made in Crellin—an organic chemistry laboratory. Crellin is a rectangular three-story building joined by an annex to Gates, an older two-story chemistry building, as shown in Figure 8. The main exhaust vent and 31 fume hood outlets are on the roof of Crellin; the main intake vent is at ground level, as shown in Figure 9. The intake and exhaust of Gates are both located on the roof.

On the day of the test, there was a variable wind blowing from the south-southwest, as shown in Figure 8. Seventy-six ml/min of pure SF_6 was released from a fume hood in Room 357 Crellin for 20 min. This fume hood exhaust is located in the southwest corner of Crellin as indicated in the photographs and has a flow rate of 690 ft³/min. Thus, the exhaust concentration in this case was 3.9×10^{-6} . Samples were taken in the first-floor hallways of Crellin and Gates and in the annex hallway between Crellin and Gates. Results are shown in Figure 10.

The highest concentrations were recorded in Crellin and the lowest in Gates, contrary to intuition which suggested the wind direction would carry exhaust fumes over to the Gates inlet vent. Results are summarized in Table III. The dilution factors are relatively high, due mainly to the fact that the intake vent of Crellin is not on the roof (where the fume exhausts are), but at ground level.

To illustrate the usefulness of dilution factors, consider a student in Spalding running a reactor with chlorine gas, for which the minimum safe level is 1 ppm. Using a minimum dilution factor of 100, the fume hood exhaust should have no higher concentration than 10^{-4} . Since a typical fume hood flow rate is 10^7 ml/min, the student should not be allowed to run chlorine gas at any flow rate higher than 1000 ml/min.

Table III. Results of Crellin Fume Hood Release

Location	Dilution factor	t_{exp} , min
Crellin, first floor	4×10^4	12
Annex, first floor	1.4×10^5	17
Gates, first floor	6×10^5	37

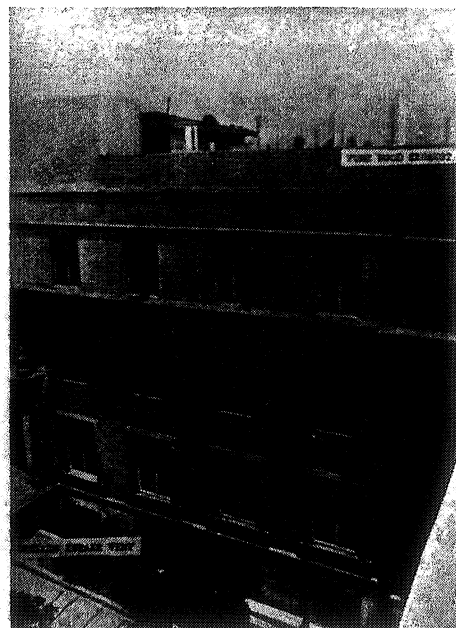


Figure 9. West side of Crellin, showing the fume hood outlet from Room 357 and the ground-level ventilation intake

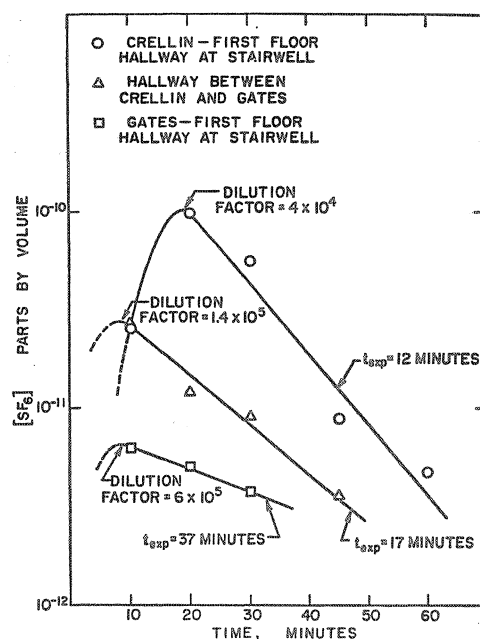


Figure 10. Results of the fume hood release of SF_6 from Crellin Room 357

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Aerosol Density Measurements Using a Modified Spiral Centrifuge Aerosol Spectrometer

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■ A spiral centrifuge aerosol spectrometer using a partial Archimedean spiral has been built and calibrated to define aerosol aerodynamic size and particle density. This instrument can define aerodynamic diameters from 0.1-10 μm with a resolution of 5%. Particle aerodynamic size, a function of particle density, shape, and size, must be determined to estimate potential inhalation hazards and when calibrating field air samplers, such as impactors and cyclones. Initially, the instrument was used to define aerodynamic size characteristics of test aerosols used for calibrating size-separating air samplers and aerosols of major air pollution importance. This instrument has measured individual densities of 3.83, 2.53, and 1.37 g/cm^3 for spherical particles of fly ash, iron oxide, and methylene blue-uranine, respectively.

It is necessary to describe aerosol aerodynamic properties to define inhalation hazards accurately and to predict performance of air-cleaning equipment. Previous work using the conifuge has been reported by Sawyer and Walton (1950), Keith and Derrick (1960), Tillery (1967), and Moss (1971). Stöber and Flachsbart (1969) combined the spiral channel concept with the separating qualities of the conifuge by rotating a spiral channel cut in a horizontal plane.

This paper describes the design and calibration of a modified, spiral centrifuge aerosol spectrometer (spiral), and use of the instrument to measure the density of spherical fly ash, iron oxide, and methylene blue-uranine particles.

Design

Figure 1 is a schematic drawing of the Los Alamos Scientific Laboratory (LASL) spiral. There are two airflows into the rotating head. Clean air for the laminating air layer enters at a controlled rate through the main bearing housing. The test aerosol is drawn through the aerosol inlet bearing assembly and the center inlet, entering the spiral channel near its central

wall. The aerosol is collected on a 6-ft-long foil placed along the outer edge of the channel.

The LASL spiral was built mainly to incorporate a deeper channel. This change stemmed from the extensive theoretical calculations done by Stöber at the University of Rochester (Stöber and Flachsbart, 1969). Other modifications were in the following areas: (1) the spiral channel was cut in forged, high-strength aluminum rather than titanium; (2) the outer coolant housing was omitted [modifications 1 and 2 were based on Stöber's experimental work demonstrating that the deposition patterns obtained from sampling monodisperse aerosols were not distinct at rotational speeds higher than 6000 rpm, and that at lower speeds the titanium channel and coolant housing were not necessary. These changes were fortuitous since recently, Raabe (1971) has observed that the rotating head had less tendency to heat up with the coolant housing removed.]; (3) channel shape was altered slightly to that of an

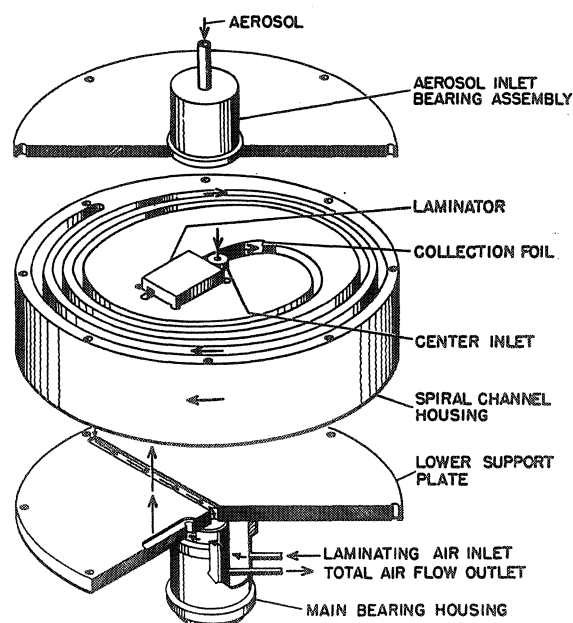


Figure 1. LASL spiral centrifuge aerosol spectrometer

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