THE EFFECT OF THE RETURN OF EXHAUSTED BUILDING AIR ON INDOOR AIR QUALITY

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Reduced ventilation in order to improve the energy efficiency of buildings has resulted in the development of significant indoor air quality problems. The need for a balance between the competing objectives of low energy costs and good air quality are perhaps nowhere more evident than in chemical laboratories, where the potential for exposure to hazardous pollutants is very great. All too often, this need has been met through reductions in the overall ventilation of the building and a reliance upon individual laboratory fumehoods to achieve acceptable air quality. In this paper, a series of experiments will be described that indicate the inadequacy of this approach.

The experiments employed sulfur hexafluoride as an atmospheric tracer of the fate of pollutants exhausted from the fumehood. The experiments indicated that reentry of fumehood exhausted pollutants had a much more significant impact on indoor air quality than direct contamination at the face of the fumehood. Reentry was seen to be especially significant when poorly planned reductions in overall building ventilation resulted in insufficient make-up air for the fumehoods. In buildings that exhibited this behavior, as much as 10% of the exhausted pollutants was returned to the building interior. During typical experiments, average building concentrations were observed to exceed 200 ppb/gr-mole released/hr under these conditions. Much higher concentrations were observed in sections of buildings where more direct reentry of exhausted pollutants was possible. Although the return fraction was reduced in more balanced ventilation systems, the indoor contamination resulting from fumehood exhaust reentry always exceeded that due to direct contamination at the face of the fumehood.

I. Introduction

It has only recently become clear that accurate assessment of exposure to airborne pollutants requires an understanding of the relationship of indoor air quality to that outdoors. The indoor concentrations of externally generated pollutants are generally less than the ambient concentrations due to physical or chemical loss mechanisms and limited air exchange rates. It has long been recognized, for example, that exterior ozone concentrations are typically greater than those indoors due to destructive reactions that occur on the interior walls (e.g. Shair and Heitner, 1974). The indoor concentrations resulting from pollutants generated within a building, however, are typically greater than ambient concentrations due to limited ventilation of the building interior.

Nowhere is there a greater potential for adverse health effects due to internally generated airborne contaminants than in chemical and biological laboratories where hazardous materials are handled. In an attempt to limit the indoor air quality problems, these materials are typically handled in fumehoods which exhaust the contaminated air directly to the atmosphere. Fumehoods are designed to reduce only the direct exposure of the laboratory personnel handling the hazardous material. As pointed out by Shair et al. (1981), however, the most significant exposure typically occurs indirectly through the return of the exhausted pollutants to the building.

This problem has been aggravated in recent years due to the desire to minimize energy costs associated with the heating and cooling of building air. This has typically led to efforts to reduce the building exchange rate with the exterior air. While the economic incentive to reduce air infiltration is strongest in cold climates, it is also increasingly being felt in more temperate regions due to the high cost of cooling the indoor air during the summer. Arbitrary reductions in the building ventilation rate for this purpose, however, can significantly increase the return of the contaminated air exhausted by the fumehood by imbalancing the overall ventilation system. In addition, reductions in building ventilation rates are typically dictated entirely by economic considerations and do not recognize the need to balance the associated potential for air quality degradation.

Although the indoor air quality problems associated with the return of exhausted building pollutants have been recognized, there apparently still exists an insensitivity and lack of appreciation for this problem. Fumehood effectiveness is still largely measured by face velocity and other measures which influence only the direct impact of the working material on the laboratory personnel. An illustration of the emphasis on fumehood face velocity is the current OSHA regulation specifying an average 150 fpm face velocity for workers transferring carcinogens. Recognizing the importance of factors other than face velocity, the American Chemical Society has recently issued a position statement in opposition to this regulation (C&E News, 1985).

The purpose of this paper is to focus further attention on the problem and emphasize the behavior of both typical and worst case buildings with respect to the return of fumehood exhausted air. In this paper, the results of atmospheric tracer experiments designed to probe this problem will be discussed. The tests were conducted over a period of almost 10 years and represent several hundred individual experiments in a variety of buildings. In some of the buildings, the experiments were conducted in an attempt to address known indoor air quality problems. Other experiments were conducted in buildings exhibiting no known air quality problems, however, in an attempt to define typical behavior. Taken together, these experiments indicate the range of significance of the return of exhausted air on indoor air quality and can be used to guide the thinking of health and safety personnel at laboratory facilities.

II. Experimental Procedures

All of the experiments employed what has become the standard technique for establishing the characteristics of the transport and dispersion of pollutants around buildings. In this technique, sulfur hexafluoride, an inert, non-toxic, colorless, odorless gas, is used as a tracer of the airborne contaminants. Sulfur hexafluoride can be detected at concentrations as low as 1 part in a trillion parts air (1 ppt) by electron capture gas chromatography. Release of a very small amount of this gas can thus be monitored throughout a building and the surrounding area. Typically the experiments were conducted semi-continuously, with a release of sulfur hexafluoride at the rate of 0.02 to 0.1 l/min over a period of an hour to a day. Air samples at various locations in and around the test building were collected using 30cc disposable plastic syringes for later analysis by the electron capture detector. In some instances, the samples were collected automatically by a time averaged sampler, while in others, support personnel were employed to collect essentially instantaneous samples manually. Additional information about the technique and its application can be found in Drivas et al. (1972) and Drivas and Shair (1974). Complete details of the analytical procedures can be found in Drivas (1974) or Lamb (1978).

The experiments directly provide the concentration at the sampling site due to transport and dilution from the source. The concentrations can be normalized with respect to the release rate of the sulfur hexafluoride and then applied to other pollutants if their emission rate is known. Modeling of the tracer results allows estimation of the air exchange rate between the building and the outside air and the fraction of the contaminants returned to the building. Simple well-mixed compartment models were employed in recognition of the relatively rapid mixing of individual rooms and even entire buildings when compared to the time scales of the experiments. Turbulent velocity fluctuations in a "stagnant" room often exceed 10-20 feet per minute, indicating the characteristic mixing time for a typical room to be of the order of a minute.

III. Presentation and Discussion of Results

A. Evidence for the Reentry Problem

Let us first examine a particular experiment conducted on the campus of the California Institute of Technology, Pasadena, CA, and identify the characteristics of the reentry problem and compare the direct and indirect (i.e. reentry) paths of fumehood pollutant exposure. The concentrations observed near the fumehood under examination and in the center of the same room during a typical experiment are displayed in Figure 1. In an attempt to identify an upper bound to the direct exposure of fumehood workers to the contaminants within the fumehood, the fumehood air was stirred vigorously. Attempts to "pull" the fumehood air into the room were monitored by instantaneous air samples collected near the face of a person located at a typical working position at the fumehood. As shown in the figure, the concentration of tracer near the face of the fumehood fluctuated but a maximum concentration of 4800 parts-per-trillion (ppt) was observed with an average over the first 5 minutes of 680 ppt. These values, when normalized with respect to the tracer release rate indicated that a 1 gr-mole release of a chemical in the fumehood would have resulted in an average exposure to the worker at the fumehood of about 2.8 parts-per-billion (ppb). Note, however, that between 4 and 10 minutes after the start of the release, there was a steady increase in tracer concentration both near the fumehood and in the center of the room. Samples collected elsewhere in the interior of the building and outside indicated that the increase was the result of contamination of the building intake air with the fumehood exhaust. This return of exhausted air resulted in an apparent steady state sulfur hexafluoride concentration of about 6000 ppt, which corresponded to 25 ppb/gr-mole released per hour, or an order of magnitude greater than the average direct exposure at the fumehood.

In each of the several hundred experiments conducted, the exposure due to the return of the exhausted air exceeded the direct exposure from any fumehood meeting minimal face velocity requirements. The steady state concentrations associated with the return of the fumehood exhaust were as low as 1-10 ppb/gr-mole released/hr in the best buildings tested. Even in these buildings, however, it was clear that a significant source strength (e.g. many fumehood activities conducted simultaneously) could result in parts-per-million (ppm) levels of pollutants in the building. In the worst buildings, however, the steady state reentry concentrations were as high as several hundred ppb/gr-mole released/hr, and it was in these buildings where indoor air quality problems were often reported. The worst buildings were typically those that did not provide sufficient make-up air for the fumehoods, resulting in a net building ventilation imbalance.

B. Mechanism of Exhaust Reentry

The reentry problem identified in the previous section is the result of the interaction of the fumehood exhaust with the building wake. As shown in Figure 2, the wake resulting from the flow of the wind around the bluff body represented by the building typically encompasses the majority of the building surface. The wake tends to be well-mixed with a characteristic mixing time of the order of a minute (Drivas and Shair, 1972). In addition, the wake is only weakly coupled to the external freestream air in that air exchange between the wake and the external air also occurs on the time scale of about a minute (Drivas et al., 1972) Thus, pollutants emitted from the building into this wake are typically mixed throughout the wake allowing the contaminated air to be returned to the building through normal ventilation system intakes or infiltration.

It has long been recognized that the solution to this problem is ensuring penetration of the building wake through to the freestream by the fumehood exhaust (e.g. Halitsky, 1968). Unfortunately, the practical and esthetic limits on stack height and exit velocities reduce the applicability of this approach for many laboratory buildings. Smith (1978), however, indicated that the replacement of flush vent exhausts with a small stack of order 10% or less of the building height and an exit velocity of greater than twice the wind speed will significantly reduce the recirculation and reentry problem. As will be indicated in the next section of the paper, however, the most significant factor in the reentry of exhausted pollutants is the balance between ventilation intake and the fumehood exhaust air. Imbalance results in infiltration throughout the building surface ensuring the intake of contaminated air from the building wake.

C. Analysis of Examples of the Reentry Problem

Balanced Ventilation Systems

Let us first examine a series of experiments that were conducted in a Chemical Engineering laboratory building on the campus of Louisiana State University, Baton Rouge, LA. The experiments illustrate the reentry characteristics of buildings exhibiting approximate ventilation system balance and indicate the validity of assumptions such as well-mixedness. The building ventilation system is designed for total recycle of the building air to reduce the energy costs associated with the introduction of fresh air into the building. Fresh air is provided, however, in the form of separate air intakes to balance each fumehood exhaust and by a separate ventilation system for parts of the first floor. In terms of exhaust reentry, this arrangement should be ideal in that the building is in balance and the intake of potentially contaminated outside air is at a minimum.

During the experiments, 0.5 l/min of sulfur hexafluoride was released from a fumehood in a laboratory on the second floor of the three story building. The fumehood exhausts and intakes are located on the roof of the building. Tracer concentrations observed within the building at representative locations on each of the three floors during one of the experiments conducted during mid-summer are displayed in Figure 3. Note that the concentrations and dynamics of each of the locations were remarkably similar. The average tracer concentrations observed between 15 and 45 minutes at all sampled locations in the building are summarized in Table 1. The average steady-state building tracer concentration was 500 +/- 160 ppt (5 ppb/gr-mole released/hr), a factor of only about 3000 less than the fumehood exhaust concentration. The uniformity of the observed concentrations validates the assumption of well-mixedness in the building. At the conclusion of the tracer release, the concentration in the building decreased exponentially at a rate consistent with one air exchange every 27.5 minutes. These data suggest an effective ventilation rate of 5,490 l/s in the 9,000 m^3 building. Employing the observed well-mixedness in the building, a mass balance on the tracer indicated that about 0.7% of that released was returned to the building. Thus, although the vast majority of the tracer was effectively exhausted from the building, the return of a small amount of material led to potentially significant indoor concentrations.

Table 1

SF6 Average Concentration (ppt)

Location	Average	No. of data points
3rd fl hall-1	580	4
3rd fl room	560	4
3rd fl hall-2	580	3
2nd fl room-1	270	3
2nd fl room-2	460	9
2nd fl room-3	360	2
2nd fl room-4	780	2
1st fl hall	400	3
	500 +/- 160	

A model of the building ventilation system composed of two interacting well-mixed stirred tanks was developed. One of the well-mixed tanks represented the building while the other represented the wake. Employing the observed steady state building concentration, the observed exponential decay rate and a typical value of a wake exchange time of 1 minute, the model predicted the solid curve in Figure 3. The generally good agreement between the model and the experiment suggests that the reentry mechanism is at least consistent with the postulated building-wake interactions.

A second experiment during lighter and more variable wind conditions during the winter verified the above estimate of the effective ventilation rate for the building. Observed concentrations and the fraction of released tracer returned to the building, however, were lower by about a factor of two during this test. This reduction was presumably due to the relative buoyancy of the exhaust air during the winter and the contaminant dilution resulting from the variability of the flow. The change of only a factor of two despite the changes in ambient meteorology suggests that the reentry is relatively insensitive to external conditions.

The effect of meteorology on fumehood exhaust reentry was observed in more detail in a series of experiments conducted in a Chemistry building at the University of California at Santa Barbara. During a typical test, the tracer was released continuously from a laboratory fumehood and hourly-averaged samples were collected. High concentrations were observed inside the building during the day, but nighttime tracer levels were barely detectible. Analysis of the tests and the associated meteorological conditions indicated that the following factors were the cause of the reduced nighttime concentrations: 1) low wind speeds at night reduced entrainment within the wake, 2) comparatively cool ambient temperatures increased the relative buoyancy of the fumehood exhaust, and 3) the direction of the nighttime winds reduced the exhaust-intake interaction. Although the wind direction tends to have a small effect on fumehood exhaust reentry due to the large portion of the surface contained within the building wake, the consistent winds of a coastal region can be used to advantage in the placement of intake and exhaust vents. The data also indicated that rainfall significantly increased the reentry concentrations due to heat and momentum transfer with the falling rain, resulting in reductions in plume momentum and buoyancy relative to the freestream.

Imbalanced Ventilation Systems

Let us now compare and contrast this behavior with that of buildings exhibiting imbalanced ventilation systems by considering an experiment at the Jet Propulsion Laboratory, Pasadena, California. Detailed information about the experiment is contained in Reible (1982). The building selected for study was designed to be at a slight positive pressure, but the ventilation system was imbalanced by a high volume fumehood in a room in the southeastern corner of the building. The exhaust rate exceeded the design intake rate in this room by about 1600 l/s. A tracer release conducted from the fumehood in this room resulted in the reentry of the exhausted air into the building by two distinct mechanisms, contamination of the building intakes as described above, and infiltration to offset the local imbalance in the southeastern end of the building.

Contamination of the two building intakes was also complicated by the geometry of the building. One building intake was influenced only by the well-mixed external wake, while the other was located in close proximity to the fumehood exhaust and thus was exposed to exhausted air before sufficient time had elapsed to mix the wake effectively. One ventilation system, therefore, was contaminated by the approximate 1% reentry indicated as typical in the previous section of the paper. Higher concentrations (about

5.5 ppb or 89 ppb/gr-mole released/hr) were observed in the intake air influenced more directly by the fumehood exhaust. With an intake rate of 3880 l/s, this suggests that about 6% of the exhausted tracer was reintroduced to the building through the intake located close to the fumehood exhaust.

Compounding the reentry problem in this building, however, was the extreme ventilation system imbalance in the rooms near the test fumehood. The negative pressure induced within the building resulted in rapid infiltration of the tracer through doors and windows back into the building. About 5% of the released tracer was returned to the room from which the tracer release was made. In this manner, room concentrations as high as 15 ppb (235 ppb/gr-mole released/hr) were observed. Thus the room concentrations were only a factor of 20 below the fumehood exhaust concentration. It is this problem which must be considered when reducing the fresh air ventilation rate for energy conservation purposes.

IV. Summary and Conclusions

Summarizing the characteristics of exhaust reentry in buildings which exhibit approximate ventilation system balance, returned pollutant concentrations are typically in the range of 1 - 10 ppb/gr-mole released/hr. The entire volume in a balanced ventilation system can generally be treated as well-mixed due to the uniformity of the wake concentrations and the generally limited localized infiltration. Typically, on the order of 1% of the exhausted air is returned to the building, a dilution factor of only 100 between exit and reentry. Additional dilution occurs, however, since the returned material is dispersed throughout the building. The total dilution is given by the fraction of exhaust returned multiplied by the ratio of the total volume flows through the building and fumehood. Significant reductions in the returned concentrations can be achieved by increasing the velocity and temperature of the exhaust relative to the ambient air to reduce wake entrainment. Note that improvements in the fumehood face velocity or similar measures will have little impact upon the reentry problem, which poses the greatest threat to indoor air quality. In fact, increases in fumehood flow may exaggerate the problem by driving the ventilation system out of balance.

In buildings that exhibit ventilation system imbalances or where the building exhausts are in close proximity with intakes, the reentry problem is much more severe. Returned pollutant concentrations can be as high as 2-300 ppb/gr-mole released/hr and the fraction of air returned can be as high as 10-15% of that exhausted. For such buildings, correction of the cause of the enhanced reentry offers the only effective means of improving the indoor air quality. Fumehood modifications such as increasing face velocity will not prove effective.

Acknowledgements

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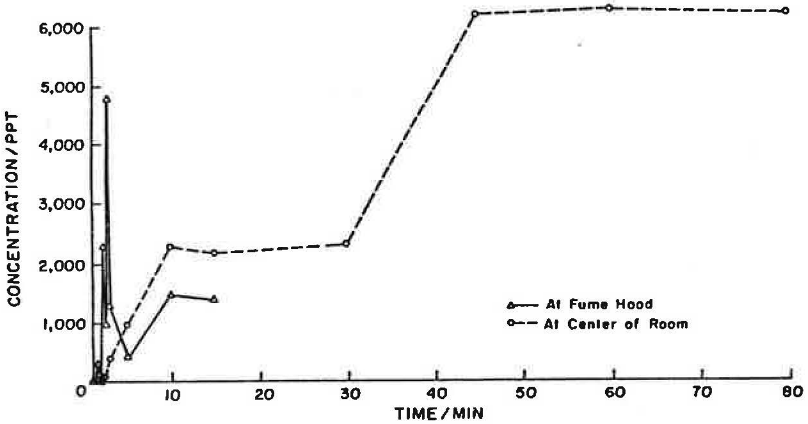
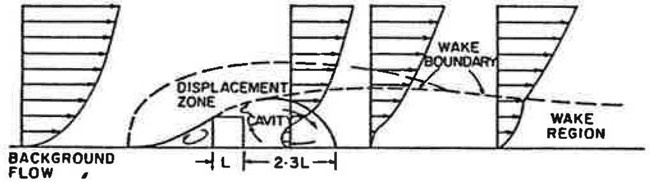
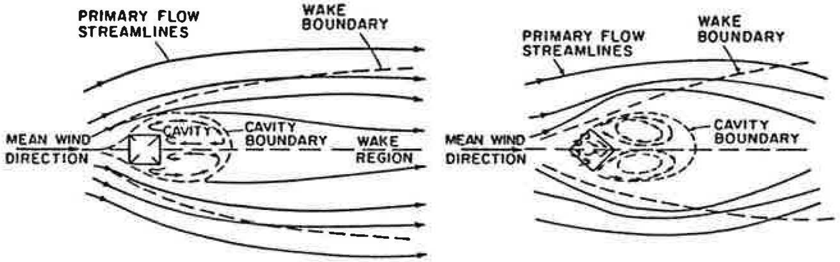


FIGURE 1. COMPARISON OF CONTAMINATION LEVELS CLOSE TO THE FUME HOOD WITH THOSE IN THE CENTER OF THE SAME ROOM DURING A TYPICAL EXPERIMENT



VELOCITY PROFILES



PLAN VIEW – 90° WIND ATTACK ANGLE

PLAN VIEW –45° WIND ATTACK ANGLE

FIGURE 2. DEPICTION OF FLOW STRUCTURE AROUND A BUILDING

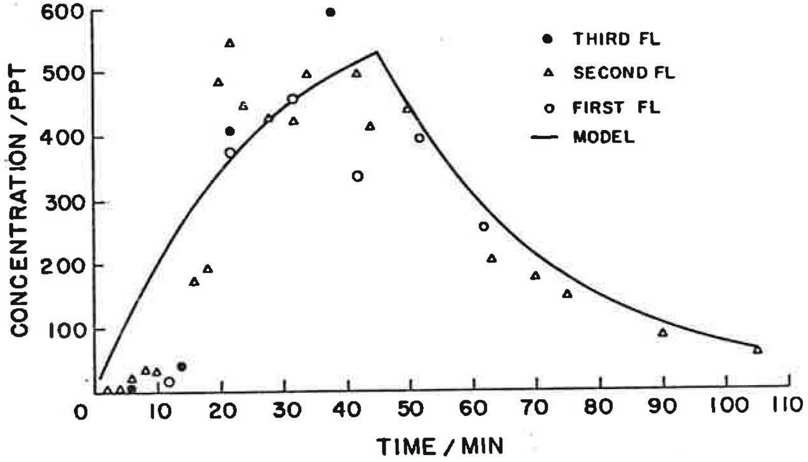


FIGURE 3. COMPARISON OF MODEL PREDICTIONS AND OBSERVED CONCENTRATIONS IN A TYPICAL BUILDING