A TRACER LABORATORY FOR UNDERGRADUATE ENVIRONMENTAL ENGINEERING PROGRAMS

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I. INTRODUCTION

Environmental engineers are often involved in field work to assess the impacts of environmental problems. While traditional lectures and problem-solving exercises serve as the basis of most college-level courses in environmental engineering, “hands-on” projects are necessary to provide students with additional skills to succeed as professionals after graduation. The purpose of this paper is to describe a novel application of atmospheric tracer technologies to enhance laboratory facilities in environmental engineering. With a minimal amount of inexpensive, specialized equipment, tracer experiments can be conducted throughout the curriculum to complement traditional lectures and problem-solving exercises for fundamental topics such as mass balance, unit conversions, dispersion of pollutants, risk analysis, indoor air quality, and ventilation. Section II contains background on tracer technologies while Section III specifies equipment and layout for a field experiment. Example applications are described in Sections IV, and conclusions follow in Section V.

II. BACKGROUND

For a typical tracer study in the field, experiments are conducted in which air parcels are tagged with a tracer gas. The air parcels are tracked while measuring concentrations downwind of the source, and by investigating how the tracer behaves, we learn how pollutants are advected and diluted by the atmosphere.

As reported by Gifford, substances used as tracers by early researchers include Kleenex lint, dandelion seeds, balloons, smoke puffs, and soap bubbles.[1] Shortcomings associated with these tracers are non-negligible mass constraints in addition to detection and measurement limitations. During the past decade, however, significant developments have been made in gaseous tracer technologies. Compared to particles or balloons, non-reactive gases are more likely to truly follow the airflow, and tracer gas detection systems have been designed to measure concentrations as small as a few parts-per-trillion-by-volume (pptv) and to measure concentrations in real time. Sulfur hexafluoride (SF_6) is one of the preferred tracers because it is chemically inert, nonflammable, non-radioactive, odorless, insoluble in water, and easily measured using electron capture detection.[2] In addition, SF_6 is man-made with no natural sources in the environment. With a low background concentration in the atmosphere, approximately 3 pptv[3], sulfur hexafluoride is a minor contributor to predicted global warming.

To date, tracer technologies have been used primarily by researchers to obtain data for developing and testing relationships that predict transport and diffusion of air pollutants. The following sections, however, describe equipment and applications of a tracer laboratory for educating undergraduate environmental engineering students.

III. EXPERIMENTAL DESIGN

Figure 1 shows the general layout of a simple tracer experiment in the field to simulate the dispersion of a pollutant from an isolated, ground-level source. Tracer gas is released at a controlled, metered rate, while air samples are collected over time at fixed locations downwind of the source. Because the spread and location of the plume are strong functions of atmospheric conditions, a meteorological station is equipped to monitor temperature, wind speed, and wind direction throughout the experiment. The air samples are subsequently analyzed using a calibrated instrument, and the data are interpreted in terms of the crosswind concentration distributions.

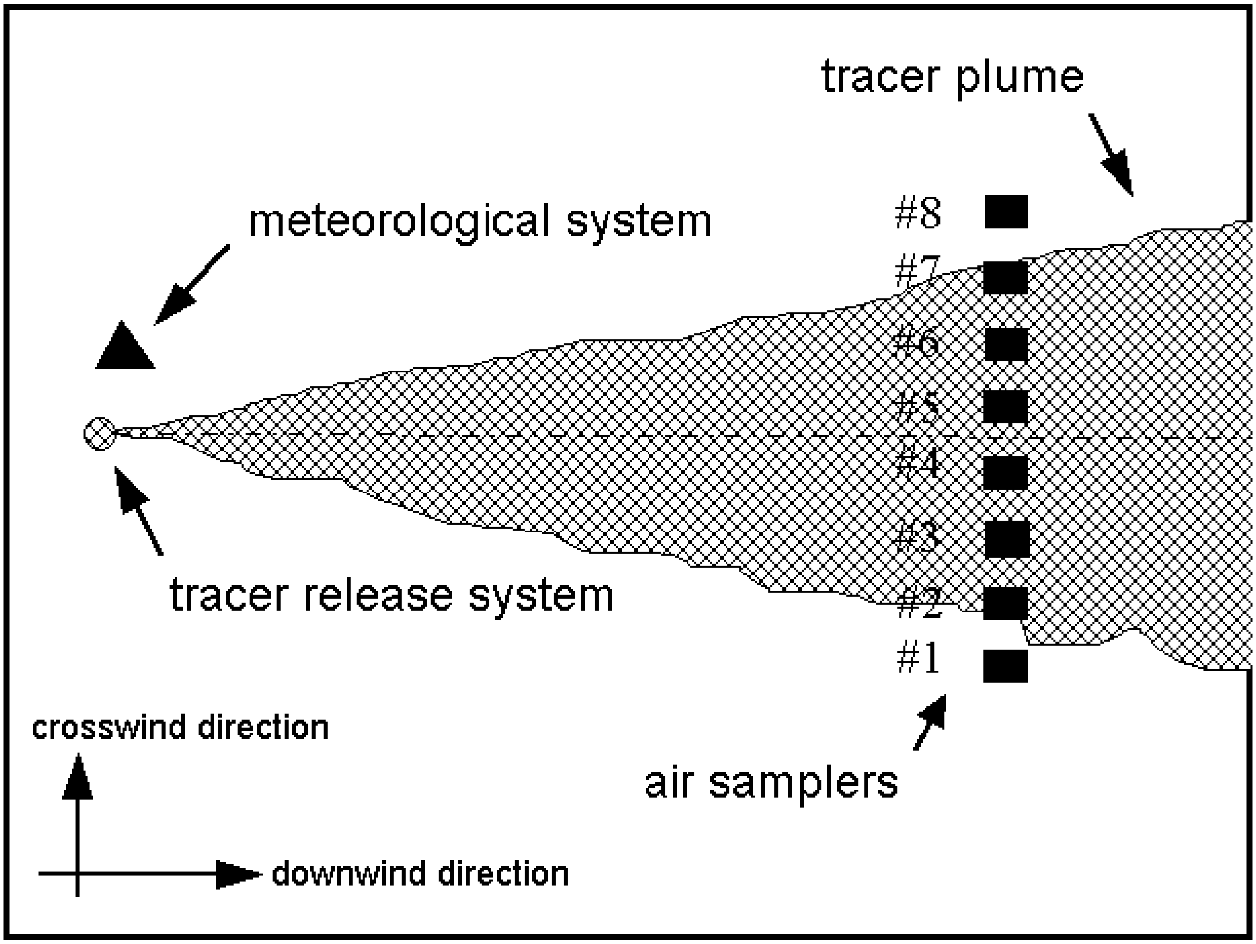

Figure 1. A top view of the typical layout for a tracer experiment to investigate the transport and spread of a plume in the atmosphere with a crosswind array of eight air samplers.

Equipment necessary to conduct this type of experiment include: a tracer release system, air samplers, a tracer analyzer, a gas calibration system, and a meteorological system.[6] Each of these components is described as follows.

The tracer release system may range from a lecture bottle of pressurized SF_6 to a computer-controlled release system such as described by Ballard or by Peterson (et al.).[7,8] For a limited number of short-range experiments in which samples are collected close to the source, or for an indoor air quality study in which ventilation patterns are investigated, only small amounts of tracer are usually necessary. In these situations, a lecture bottle (with a regulator and calibrated rotameter) is sufficient. A lecture bottle is a small, pressurized gas cylinder, approximately 15 inches long and 2 inches in diameter. In a full-scale field study, however, larger amounts of tracer must be released over longer time periods to produce detectable concentrations hundreds or thousands of meters downwind. Ballard's computerized system utilizes a mass flow controller and a mass flow meter to control and monitor the release rate of SF_6 from a pressurized gas cylinder while the data acquisition system consists of a notebook computer, an analog-to-digital (A/D) system, and LabVIEW® software.

Plastic disposable syringes are used to collect air samples downwind of the source, and a new robotic sampler was developed at Montana Tech to collect syringe samples over time periods between one and 60 minutes. In this design, a magazine holds up to six 30-cc syringes for sequential sampling. A keypad and liquid crystal display allow the user to interface with a microprocessor to select sample size, delay time before collecting the first sample, time interval between samples, and sample duration.[9] During a sampling period, a stepper motor extracts the plunger of a syringe. At the end of each sampling period, a cap is fired onto the inlet of the syringe, and the capped syringe drops into the bottom of a metal enclosure.

For analyzing the syringe samples, a portable SF_6 analyzer is available from Rydock Scientific.[10] This "microanalyzer" is a modified version of the design by Benner and Lamb.[11] In the flow stream, sample air is mixed with hydrogen and passed through a catalytic reactor. The source of hydrogen is a small, rechargeable hydride cylinder that holds approximately 30 L of hydrogen. In the reactor, the hydrogen combines with oxygen in the sample stream to form water, and the water is subsequently removed in a Nafion counter-current dryer. The purge gas for the dryer can be ambient air or nitrogen from a pressurized gas cylinder. The SF_6 in the flow exiting the dryer is measured with an electron capture detector (ECD), and pumps are located at the downstream end of the flow system to minimize dead volume and response time (approximately 0.5 s). The output from the ECD is an analog voltage signal (0-5 V) which can be directed to a data acquisition system for storage. The lower detection limit with the Rydock Scientific microanalyzer is about 5 pptv. The instrument weighs 4.5 kg, is 46 cm by 15 cm by 30 cm in size, and can operate on battery power in the field. It may be used in two modes: 1) as a post-sampling analyzer to determine time-averaged SF_6 concentrations in syringe samples, or 2) as a real-time monitor to measure tracer concentrations in the field.

Calibrations of the microanalyzer are performed using compressed gas cylinders of certified gas standards. The ECD voltage response is recorded for each standard gas to determine the relationship of "SF_6 Concentration versus ECD Voltage Response". Calibrations are performed before and after field experiments using a calibration manifold, with standard concentrations encompassing the range of field data.

For indoor air quality studies, a complete meteorological system is not necessary, but pollutant dispersion in the field is strongly dependent on atmospheric conditions. A basic meteorological station consists of temperature sensors at two heights, an anemometer, a barometer, and a data acquisition system. Temperature data may be used to infer an atmospheric stability category during a tracer experiment based on the gradient of temperature with height above the surface. Wind speed and wind direction, monitored by the anemometer, are important for dilution and advection of the tracer plumes, and barometric pressure is required for unit conversions. A notebook computer with an A/D system and software such as LabVIEW® , or a commercial data logger, can be used for data acquisition.

The SF_6 laboratory facility at Montana Tech was developed primarily for undergraduate education, and students participated in the construction of many of the components described above. For example, design and testing of the computer-controlled release system were portions of a thesis project for a graduate student in the environmental engineering department. Faculty, graduate students, and undergraduate students in the engineering science department designed, fabricated, and programmed the robotic air samplers. Finally, a calibration manifold and a meteorological tower were designed and assembled by environmental engineering students during summer research appointments.

IV. APPLICATIONS

A sulfur hexafluoride laboratory is portable and versatile, and it can be used in many different courses to enhance an environmental engineering curriculum. For example, the simple experiment illustrated in the previous section is appropriate for an air diffusion modeling course in which the students may compare their field results to predictions from the Gaussian plume equation and to output from recent versions of Environmental Protection Agency (EPA) regulatory models such as SCREEN, TSCREEN, or ISC. Other experiments may be designed for an industrial ventilation course to determine room air exchange rates from the rate of decay of tracer concentrations using standard box model equations, and efficiencies and flowrates of laboratory fume hoods can be tested by injecting tracer into a hood while measuring concentrations near the face and in the ductwork. Regarding indoor air quality, sick building syndrome caused by outside sources of contamination can be investigated by releasing SF_6 near air intake vents and by collecting samples throughout the building. In a general laboratory course, the tracer equipment can be used to illustrate quality assurance principles regarding calibration, documentation, data collection, and reporting techniques for field campaigns.

These applications represent only a handful of the possible uses for a tracer laboratory in an educational arena. In addition, students are quite creative when given the opportunity to develop their own projects. For example, a class project was designed and conducted by students at Montana Tech to investigate the accumulation of cigarette smoke in the vicinity of building entrances on campus. Figure 2 shows the layout for one test consisting of three 30-min experiments. A cylinder of SF_6 with a regulator and calibrated rotameter was located near the building entrance where smokers usually stand, and three syringe samplers were positioned within and near the alcove. The samplers collected air at the following locations: 1) within the cavity at Location # 1, 2) approximately three meters from end of the building overhang at

Location # 2, and 3) approximately three meters inside the foyer at Location # 3. A UVW anemometer was used to monitor the local winds near the setup.

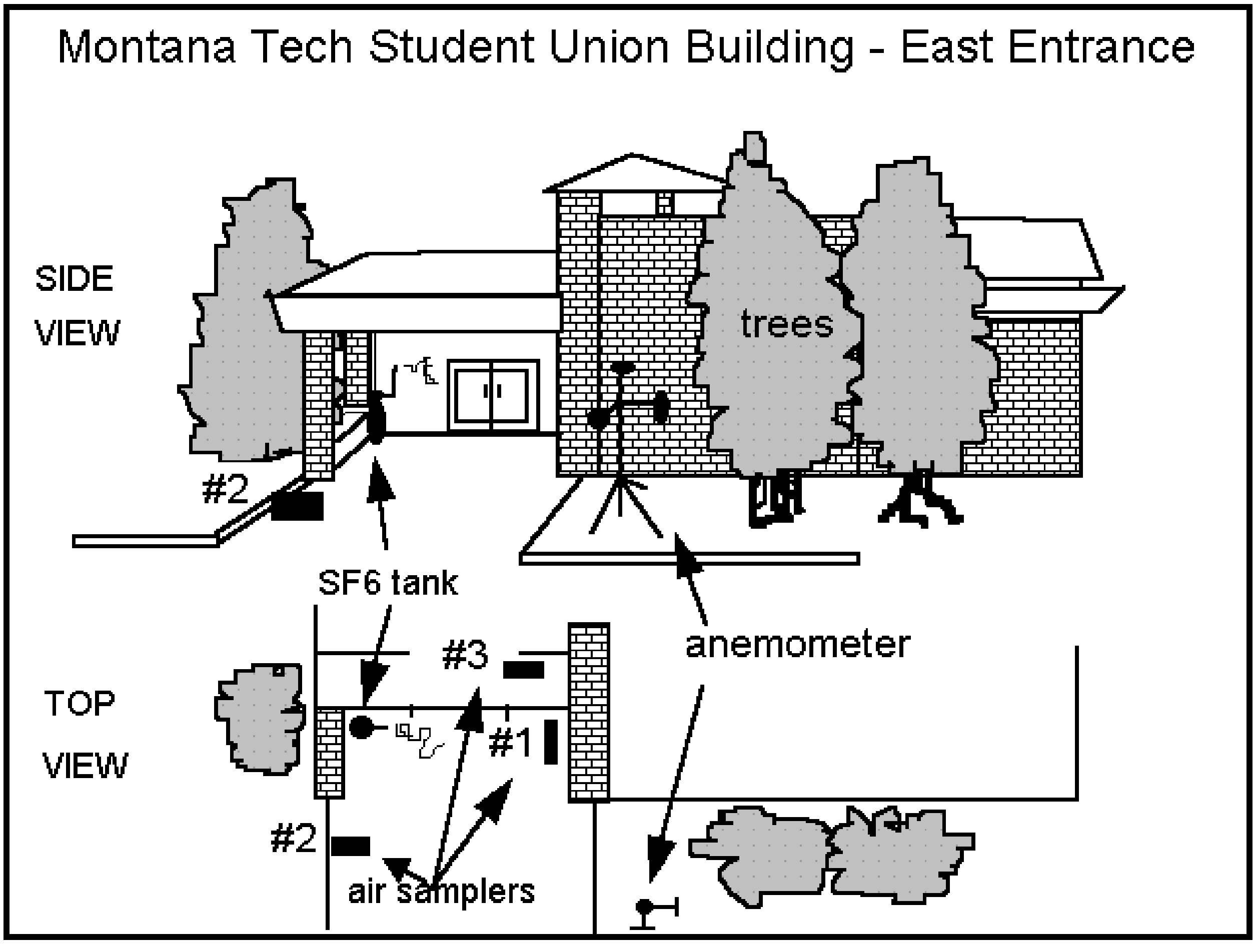

Figure 2. The layout for a tracer test on the Montana Tech campus to simulate the behavior of cigarette smoke in the vicinity of a building entrance.

During the experiments, the release rate of SF_6 was 249 mL/min, or 1.24 g/min. Meteorological data included a barometric pressure of 826.7 mb and a temperature of 293 K. As shown in Table 1, the winds near the alcove were light and extremely variable with average wind speeds less than 1 m/s and wind direction standard deviations near 100 deg. Large variability in wind direction is commonly observed when wind speeds are very low, and also in turbulent wake regions caused by flow around large buildings.

As expected, the highest concentrations in Table 1 were observed within the alcove at Location # 1, and the lowest concentrations were observed inside the foyer at Location # 3. On average, the concentrations in the alcove were approximately 2600 times higher than in the foyer, and approximately 100 times higher than outside the alcove at Location # 2. (Note: the microanalyzer provided syringe concentrations in units of pptv, but because engineering calculations often require concentration units in mass-per-unit-volume, the data were also converted to μg/m^3). During the sampling periods, one student operated the portable SF$_6$ analyzer in “real-time” monitor mode to observe the instantaneous behavior of the tracer at various positions within the sampling array. For example, inside the alcove near Location # 1, the concentrations remained relatively constant, while near Location # 2, concentrations varied intermittently from near zero to values as high as the alcove concentrations. The instantaneous exposure at Location # 3 depended, of course, on the pedestrian traffic using the entrance.

Table 1. Example Data from a Tracer Test Conducted on the Montana Tech Campus

	Experiment # 1	**Experiment # 2**	**Experiment # 3**	**Average**
Start Time of Experiment (MST)	**10:24**	**11:20**	**11:50**	**-**
Sampling Duration (min)	**30**	**30**	**30**	**30**
Average Wind Speed (m/s)	**0.69**	**0.99**	**0.80**	**0.83**
Standard Deviation of Wind Azimuth (deg)	**81**	**122**	**87**	**97**
Concentration at Location # 1 (pptv)	**7.09×10^5**	**1.24×10^6**	**8.36×10^5**	**9.27×10^5**
Concentration at Location # 2 (pptv)	*****	**8.90×10^3**	**9.23×10^3**	**9.07×10^3**
Concentration at Location # 3 (pptv)	**3.30×10^2**	**2.47×10^2**	**4.94×10^2**	**3.57×10^2**
Concentration at Location # 1 (μg/m^3)	**3.51×10^3**	**6.12×10^3**	**4.14×10^3**	**4.59×10^3**
Concentration at Location # 2 (μg/m^3)	*****	**4.41×10^1**	**4.57×10^1**	**4.49×10^1**
Concentration at Location # 3 (μg/m^3)	**1.63×10^0**	**1.22×10^0**	**2.45×10^0**	**1.77×10^0**

*** The sampler at Location # 2 malfunctioned during Experiment # 1.**

The tracer data provided a quantitative and qualitative picture of the dilution of pollutants in this alcove under these meteorological conditions, but additional calculations were performed to relate the results to concepts of ventilation and risk analysis. An average ventilation rate (Q) for the alcove with units of m^3/s was estimated from the average concentration in the alcove (C_{SF6}) using the box model equation for conservation of mass: $Q = Q_{SF6} / C_{SF6}$; where units on the release rate are ug/s, and units on concentration are ug/m ^{3}. In addition, steady-state concentrations of specific pollutants (C_p) were estimated with the box model for corresponding pollutant release rates (Q_p), where $C_p = Q_p / Q$, or directly from the ratio of the release rates as $C_p = C_{SF6} \times Q_p / Q_{SF6}$.

For example, the alcove ventilation rate based on the average concentration during the three experiments at Location # 1 was 4.5 m^3/s. This ventilation rate is important because it describes the dilution of the harmful pollutants within the cigarette smoke. In particular, acetamide is one of the cancer-causing compounds in cigarette smoke, and according to

Ecobichon and Wu, sidestream emissions contain 86-156 ug acetamide per cigarette.[12] Using the high end estimate of 156 ug/cigarette, and assuming it took seven minutes to smoke a cigarette with seven smokers in the alcove at any time, the predicted steady state concentration of acetamide is 0.58 ug/m^3. Based on a unit risk factor (R) of 2.00x10^{-5} per ug/m^3 for acetamide, the predicted cancer risk (P_e), according to the equation $P_e = C_p$ x R, is 1.2x10^{-5}, or “12 in a million” for long term exposure.[13] In other words, out of one million people continuously exposed to the concentration of acetamide predicted by our experiments, twelve people may contract cancer. A cancer risk of “one in a million” is usually assumed to be the acceptable level for industry standards; thus, the cancer risk for acetamide within our building alcove was above the acceptable level. Furthermore, acetamide is only one of many carcinogens within the smoke, and little is known about the additive or synergistic effects of exposure to multiple carcinogens.

V. CONCLUSIONS

In this paper, a tracer laboratory is described as a simple tool for improving the education of environmental engineers. A small amount of inexpensive, specialized equipment provides an unlimited source of experiments in the laboratory and in the field to corroborate lectures and homework in several classes. As a result, students acquire “hands-on” training by calibrating and operating state-of-the-art instruments while experiencing applied problem solving, quality control, and data interpretation. Students learn and retain more by actively participating in class exercises, and given the freedom to design experiments with a tracer facility, students are offered an additional outlet of creativity. Furthermore, these projects require students to learn to work as a team.

In conclusion, tracer technologies may play an important role in our educational system to prepare engineers for field and/or project work. An SF_6 laboratory is not only applicable for colleges with environmental engineering programs, but also for environmental science or meteorological programs, physics departments, and even high school science classes.

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REFERENCES

1. Gifford, F. A., 1955: A simultaneous Lagrangian-Eulerian turbulence experiment. *Monthly Weather Review*, **83**, 293-301.
2. Lamb, B., 1985: *Atmospheric Tracer Techniques*. Washington State University, Pullman, WA, 71 pp.
3. Maiss, M., L. P. Steele, R. J. Francey, P. J. Fraser, R. L. Langenfelds, N. B. A. Trivett, and I. Levin, 1996: Sulfur hexafluoride - a powerful new atmospheric tracer. *Atmos. Environ.*, **30**, 1621-1629.
4. Hanna, S. R., G. A. Briggs, and R. P. Hosker, 1992: *Handbook on Atmospheric Diffusion*. DOE/TIC-11223, 102 pp. [Available from Technical Information Center, U. S. Department of Energy, Springfield, VA 22161].

5. Turner, D. B., 1994: *Workbook of Atmospheric Dispersion Estimates: An Introduction to Dispersion Modeling.* 2nd ed. CRC Press, 192 pp.

6. Peterson, H., 1996: *The Use of SF_6 for Undergraduate Environmental Engineering Education*, Montana Tech, Butte, MT, pp.

7. Ballard, P. V., 1995: *Design and Testing of Release Equipment and Analytical Methods for Examining the Instantaneous Dispersion of Plumes.* Master of Science thesis, Montana Tech, Butte, MT, 54 pp.

8. Peterson, H. , P. Ballard, and B. Lamb, 1995: A new Lagrangian approach to studying instantaneous plume dispersion and concentration fluctuations. *Proc. 11th Symp. on Boundary Layers and Turbulence*, Charlotte, NC, Amer. Meteor. Soc., 140-143.

9. Shannon, S., 1996: *Control Software for Robot Air Sampler*. Master of Science thesis, Montana Tech, Butte, MT, 59 pp.

10. Rydock Scientific, 1995: *Microanalyzer Manual*. [Available from Rydock Scientific, P.O. Box 399, Flagstaff, AZ 86002-0399].

11. Benner, R., and B. Lamb, 1985: A fast response continuous analyzer for halogenated atmospheric tracers. *J. Atmos. Oceanic Technol.*, **21**, 582-589.

12. Ecobichon, D., and J. M. Wu, 1995: *Environmental Tobacco Smoke: Proceedings of the International Symposium at McGill University*. Lexington Books, U.S.A., 3-56.

13. *User's Guide to the Assessment of Chemical Exposure for AB 2588 (ACE2588) Model Version 92092.* Prepared by Applied Modeling Incorporated for County of Santa Barbara Air Pollution Control District, Goleta, CA.

BIOGRAPHICAL INFORMATION

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