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A MultiTracer System for Multizone Ventilation Measurement

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ABSTRACT

Mass transfer due to pressure-driven air flow is one of the most important processes for determining both environmental quality and energy requirements in buildings. Heat, moisture, and contaminants are all transported by air movement between indoors and outdoors as well as between different zones within a building. Measurement of these air flows are critical to understanding the performance of buildings. Virtually all measurements of ventilation are made using the dilution of a tracer gas. The vast majority of such measurements have been made in a single zone, using a single tracer gas. For the past several years LBL has been developing the Multi-Tracer Measurement System (*MTMS*) to provide full multizone air flow information in an accurate, real-time manner. MTMS is based on a quadrupole mass spectrometer to provide high-speed concentration analysis of multiple tracer gasses in the (low) ppm level which are injected into multiple zones using mass flow controllers. The measurement and injection system is controlled by a PC and can measure all concentrations in all zones (and adjust the injected tracer flows) within two minutes and can operate unattended for weeks. The resulting injection-rate and concentration data can be analyzed to infer the bulk air movement between zones. The system also measures related quantities such as weather and zonal temperature to assist in the data interpretation. Using MTMS field measurements have been made for the past two years.

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INTRODUCTION

Tracer gasses are used for a wide range of diagnostic techniques including leak detection[1,2] and atmospheric tracing.[3] One application which has had a resurgence in the last decade is the use of tracer gasses to measure ventilation (i.e., air flow) in buildings.[4] Ventilation is an important process in buildings because of its impact on both energy requirements and indoor air quality—which are both topics of concern to society. Measurement of the tracer gas concentration and injection combined with conservation laws allows a quantitative determination of the tracer transport mechanism (i.e., a *measurement* of the air flow).

The vast majority of the ventilation measurements made to date have involved a single-tracer gas deployed in a single zone. This technique has proven very useful for buildings which may be treated as a single zone (e.g., houses) and for more complex buildings in which there are isolatable sub-sections. However, as the need to understand more complex buildings has grown, tracer gas techniques that are able to treat multiple zones have been developed.[5] Multizone techniques recognize that not only does air flow between the outside and the test space, but that there are air flows between different parts (i.e., zones) of the test space and, in the complete case, they are able to measure these flows. Accordingly, the complexity of multizone measurement techniques grows at least as fast as the square of the number of zones.

The MultiTracer Measurement System[6] (**MTMS**) has been designed to make real-time, multizone air flow in buildings. MTMS injects a controlled amount of various tracer gasses into the test space(s) and by monitoring the resultant concentration can estimate the relevant air flows. The system fills the twin needs for the determination of pollutant and energy transport.

MTMS, like all tracer-gas ventilation-measuring systems, uses the dilution (or non-conservation) of a tracer gas to infer air flows. In order to do this the system must be able to perform certain functions: injecting controlled amounts of tracer gasses into specified zones, measuring the concentration of the tracer gasses in all the zones, and storing the resultant information for later use. MTMS is able to do these functions using a PC controlled data logging and control system.

MTMS HARDWARE DESCRIPTION

The MTMS hardware is responsible for measuring the concentrations of all gasses in all zones and for injecting tracer gasses into those zones in order to effect the control strategy. The core of the system is the measurement of concentration and it is supported by plumbing and control technology. Figure 1 shows a diagram of the MTMS hardware.

Analysis of Concentrations

Accurate and timely measurement of the tracer gas concentrations is the constraint which is most demanding of the instrumentation and has required new methods. As evidenced by having its own society,[7] mass spectrometry is a well-utilized tool. Until recently, however, mass spectrometers have been too large and too costly for typical tracer gas analysis in buildings. Currently Residual Gas Analyzers (**RGAs**), quadrupole mass spectrometers, are small, reliable, and available at prices comparable to other instrumentation being used (e.g., gas chromatographs).

The zone air to be measured is selected via a manifold and pumped into a vacuum chamber in which an RGA must be housed. Pump oils are removed from the vacuum with a catalytic trap. These operations have a response time of less than one second.

The RGA itself has an absolute accuracy of about ½% of reading; however, at the pressures we are working there is electronic noise of about 20 ppb. Most tracer gasses can be calibrated to ±1% down to 2 ppm where the noise dominates the uncertainty. Gasses with large backgrounds may have to be used at higher concentrations to maintain the same uncertainty, (e.g., helium at 5.25 ppm background will have a minimum uncertainty of 53 ppb). The electron multiplyer is less sensitive to heavy ions and so it is necessary to use slightly higher concentrations for gasses such as sulfur hexafluoride. For MTMS gasses the typical target concentration (i.e., the concentration in the zone in which they are injected) are from 20 to 50 ppm to allow the non-target concentrations to be measured with some accuracy.

Gasses of interest other than the tracers, such as carbon dioxide and water, can also be monitored in the course of the experiment.

Injection of Tracer Gas

The tracer gas injection is controlled by a separate Mass Flow Controller (**MFC**) for each gas. These devices measure the mass flow with a precision hot wire anemometer (or hot films) and control a needle valve to regulate the mass flow to within 1% accuracy (full scale) in a 50:1 operating range. Response time is typically under 10 seconds, occasionally some adjustments are necessary to the controls when changing gas type or flow range. The tracer gas is often injected at multiple locations and small fans are used to make sure that mixing occurs. Poor mixing is usually the biggest source of error in the measurements. Some tubing types are incompatible with some tracer gasses, specifically MTMS uses quarter inch polyethylene tubing which has worked well with all the tracer gasses used.

Tracer Gas Selection: There are several factors governing the selection of tracer gasses. The ideal gas is non-toxic, non-flamable, inexpensive, readily available, and easy to detect. An RGA is able to detect almost any gas, giving great flexibility but also difficulties from interfering gasses. MTMS measurements have been made with up to six tracer gasses using Helium, Freon 12, Freon 13B1, Freon 22, Sulfur hexafluoride, and Butane. Other tracer gasses (e.g., noble gasses, perfluorocarbons, non-toxic volatile organics, etc.) are possible, but may be impractical.

Sampling System

Air is pumped from each zone, and outside, continuously using a *free piston* pump to a valve manifold where one air stream is selected for measurement. The tubing and pump size were matched so that it takes at most 10 seconds for zone air to reach the analysis equipment.

Care must be taken to prevent possible condensation or freezing of humid air (and so blocking the tubing) as it travels through cold areas. Usually this means that the tubing must all be inside the structure being monitored during cold weather. Additional samples (i.e., measurements not used in the MTMS control) may be taken from other locations such as attics or ducts, or near suspected leakage sites.

Computer Data Acquisition and Controls.

The various functions necessary for MTMS operation are performed via a host PC computer which communicates via serial ports to the RGA interface and a data acquisition computer. The data acquisition computer runs a simple program to interpret requests from the PC and read various voltages or temperatures, outputs the controlling voltages for the mass flow controllers, and operates the valves which select which zone is to be analyzed. Usually there is a weather tower to measure temperature, wind speed, and direction and one temperature for each zone. Other sensors may be monitored as well, such as barometric pressure, and HVAC operation.

Overall response time is limited by the serial I/O between the PC and the RGA Interface. It generally takes between 4 and 6 seconds per gas depending on the concentration. Typically for a three zone measurement it takes about 110 seconds to measure four gasses in four zones, (outside counts as a zone, and the argon reference counts as a gas).

The amount of injected tracer, F, is controlled so as to keep the concentration of each gas at a target level in one zone. A proportional-integral control strategy is used. The control is tuned to be stable toward all perturbations—especially start-up conditions. The on-line analysis is used in the control to help anticipate the response to any changes in injection.

PRELIMINARY APPLICATION

The fundamental output from MTMS is a time-series of the tracer gas injected into each zone, and the concentration each species of tracer gas in each zone.

As an example we have used a two-story, residential size structure which is naturally divided into six zones: zone 1 is a small kitchen, zone 2 is a small bedroom, zone 3 is a large open hallway, zone 4 is the living room, zone 5 is the stairway to the upper floor, and zone 6 is a very open single upstairs room. This structure is now used as a lab and all the exhaust vents have been sealed. The upstairs ceiling (zone 6) is quite leaky. All the doors between the rooms were closed for these tests. The corresponding six tracers used were Helium, Freon 13B1, Freon 12, Sulfur hexafluoride, Butane, and Freon 22. The volume of each zone was 36, 32, 60, 108, 17, 246 cubic meters, respectively. From the physical layout you would not expect any direct flow between zone 1 and 3, between zone 2 and 3, between zone 3 and 6 and between zone 4 and 6, further there should be only a small flow between zone 4 and 5.

Figures 2 displays data from a five day period in the test structure.[8] Figure 2a shows the injection rate of gas 1 and its concentration in each of the zones. Figure 2b shows the concentration of all gasses in zone 1, as well as the amount of the tracer gas injected into that zone. The concentration of the controlled gas in each zone is kept relatively stable. One can infer changes in the total ventilation from the injection; the diurnal pattern is apparent. The amount of the other tracers in each zone are an indication of the air flow between them and is constant with the physical layout. The two breaks in the data are times when the operator stopped the measurements to copy the data and make the adjustment in the gas 5 injection rate.

One measure of the robustness of the measurement system is its ability to recover from sudden large changes in the system it is measuring. To simulate this we forced the injection rate to a low value after MTMS had reached steady-state; this condition mimics a normal start-up. Figure 3 displays this data. Figure 3a is analogous to fig. 2a; the decays of the concentrations can be clearly seen as well as the increase injection and final recovery after normal control is permitted. Figure 3b shows the concentrations of each of the tracers in the zone in which it is injected (i.e. the controlled gas). (As the injection rate of gas 5 is not reduced, its concentration is not shown.) Although some oscillation can be seen, the control stabilizes. Optimal control requires knowledge about the volume, air change rate, and mixing properties of each zone. Fortunately, the analysis methodology is not sensitive to these fluctuations. If desired, fine tuning of the control parameters can be used to either decrease this amplitude or the response time of the system.

ANALYSIS METHODOLOGY

The analysis of the measured data is based on the conservation of both air and tracer gas and can be expressed by the multizone continuity equation which relates the ventilation, Q, to the concentration of tracer, C, associated injection, F and the zonal volumes, V:

$$\mathbf{V} \cdot \dot{\mathbf{C}}(t) + \mathbf{Q}(t) \cdot \mathbf{C}(t) = \mathbf{F}(t) \tag{1}$$

where the bold symbols denote matrices.

On-Line Analysis: MTMS use filtered values of the concentration and injection matrices to estimate the ventilation flows in real time. These real-time flow estimates are used by the control algorithm to keep the concentrations at target and also supply the operator with quick feedback.

Error Analysis: Uncertainties in the measured concentrations and amounts of injected tracer can be used to estimate uncertainties in the ventilation flows. Because of the coupled nature of the problem, however, the uncertainties in different elements are highly correlated. It is necessary, therefore, to represent these uncertainties by a full covariance matrix. A detailed derivation of these uncertainties has been previously published.[9]

Off-Line Analysis: The size of the uncertainties of an individual estimate of the ventilation, such as those made in the on-line analysis, can be quite imprecise. Other information, however, can be used to improve the estimate such as the requirements for continuity in time and non-negative flows. An off-line analysis procedure[10] uses the stored concentration and injection data, the physicality constraints, and a full uncertainty analysis, to get a best estimate of the ventilation flows.

Details on the on-line analysis and examples of the off-line analysis of data measured with MTMS can be found in reference 7.

ACKNOWLEDGEMENT

I would like to acknowledge the efforts of Darryl Dickerhoff, who—like any mother—was instrumental in the fabrication and was kept awake nights in and around the birth process.

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6. Sherman, M.H., Dickerhoff, D.J. "A Multigas Tracer System for Multizone Air Flow Measurements" To be published in proceedings of the Thermal Performance of Exterior Building Envelopes IV Conference, [Orlando FL, Dec. 1989], *ASHRAE* Lawrence Berkeley Laboratory Report No. LBL-26538

7. American Society for Mass Spectrometry; P.O. Box 1508; East Lansing, MI 48826

8. During this test run gasses 1-4 were controlled by MTMS in the normal manner (i.e., attempting to keep a constant target concentration in the injected zone), but the injection of gasses 5 and 6 were manually controlled. The injection rate of gas 5 was held constant until noon on July 17 when its rate was roughly doubled. The injection rate of gas 6 is constant for the duration of the measurements.

9. Sherman, M.H., "Uncertainty in Air Flow Calculations Using Tracer Gas Measurements," *Building and Environment,* Vol. 24, No. 4, pp. 347-354 (1989).

10. Sherman, M.H., "On Estimation of Multizone Ventilation Rates from Tracer-gas Measurements" *Building and Environment*, Vol. 24, No. 4, pp. 355-362 (1989)

FIGURES CAPTIONS

1 Layout of the MultiTracer Measurement System (MTMS).

2 Injection and concentration data for a six day period starting at midnight: a) shows concentrations of gas 1 in all zones; b) shows concentrations of all gasses in zone 1.

3 Injection and concentration data for a manual restart. The decay of the concentration can be seen when the injection is manually cut-down at hour 18. The ability of the system to recover after control is restored at hour 20 indicates robustness. Fig. 3a) shows concentrations of gas 4 in all zones. Fig. 3b) shows the concentration of the gas being injected into zones 1-4 and 6.

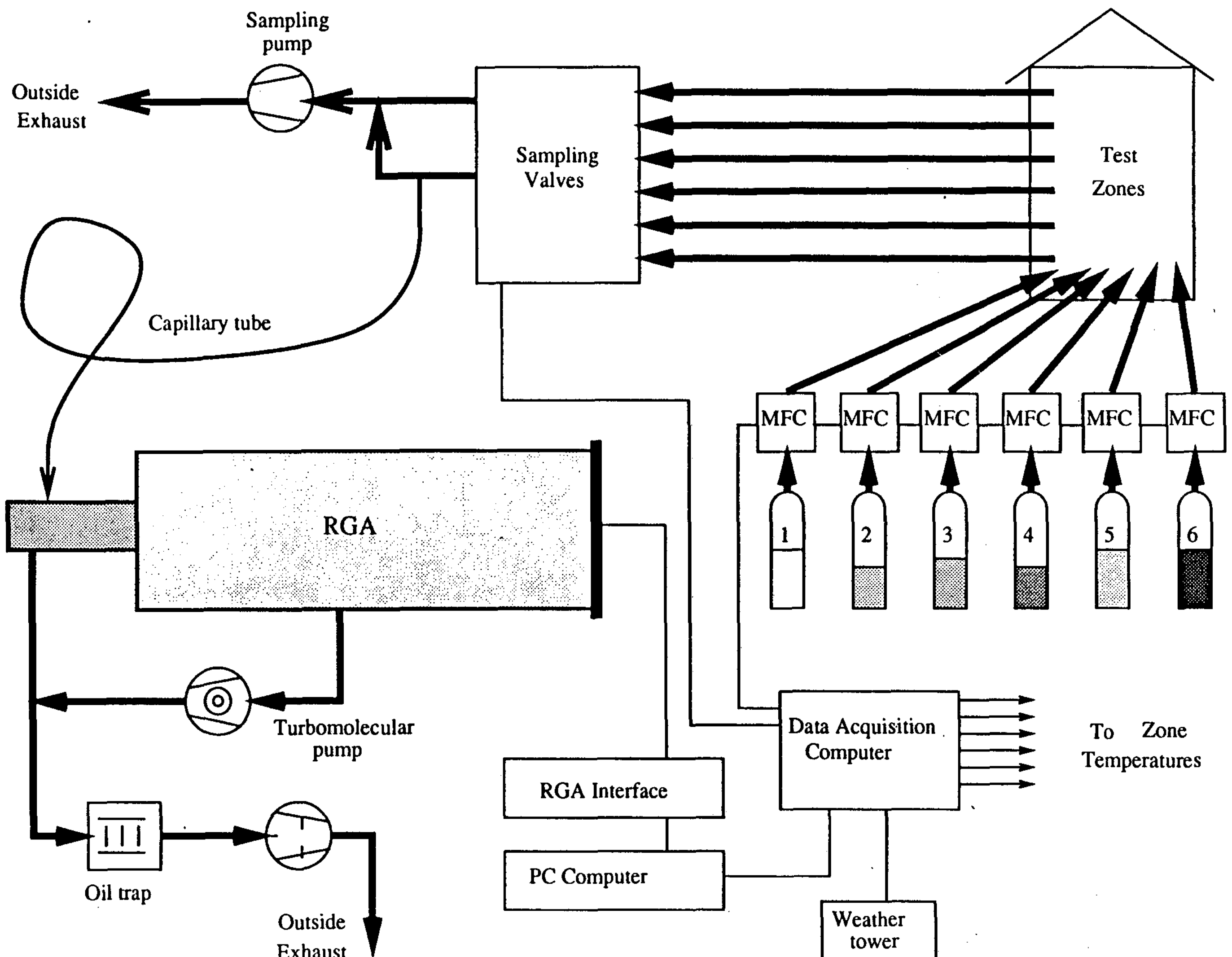

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Figure 1: Layout of the MultiTracer Measurement System (MTMS).

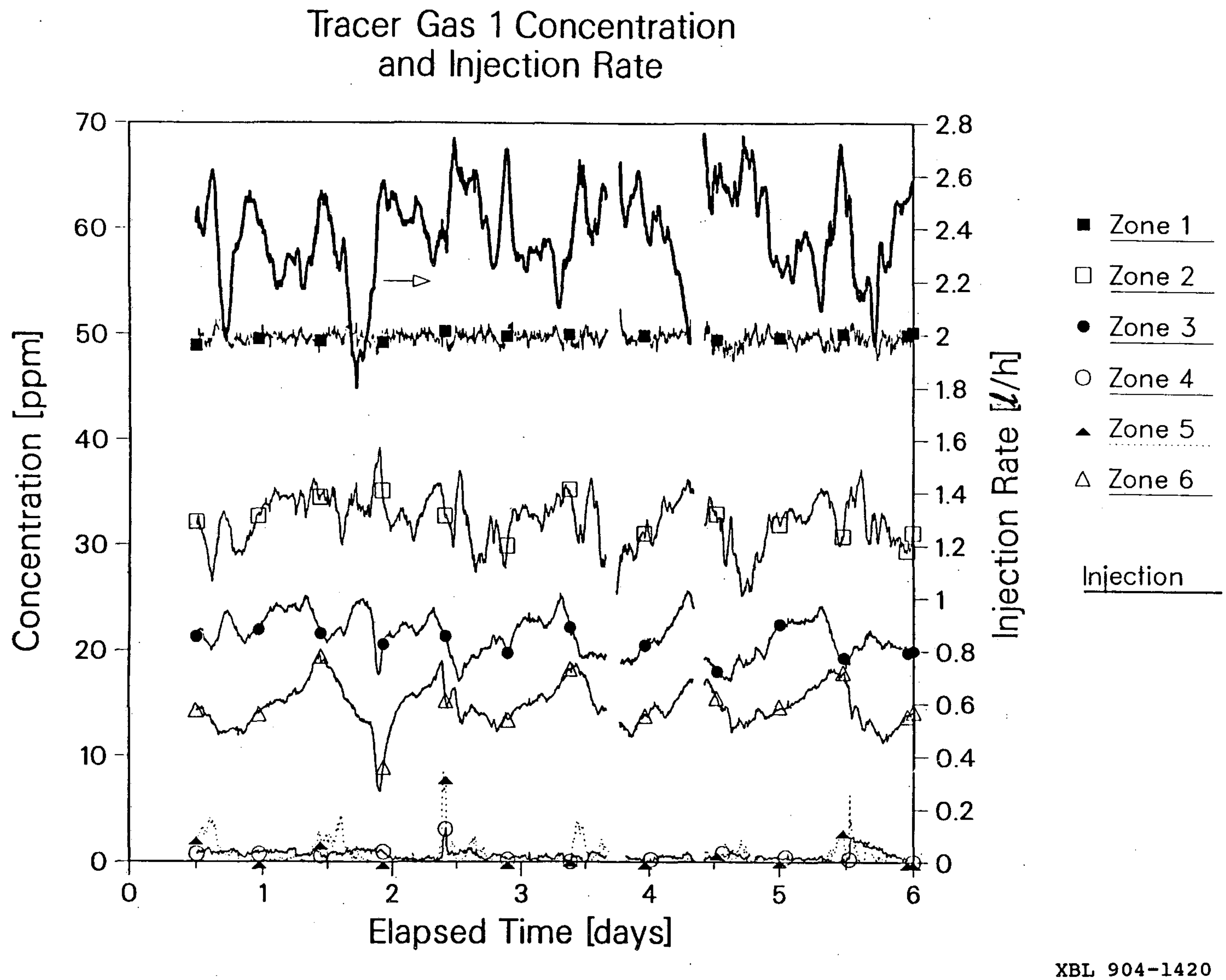

Figure 2a: Shows concentrations of gas 1 in all zones.

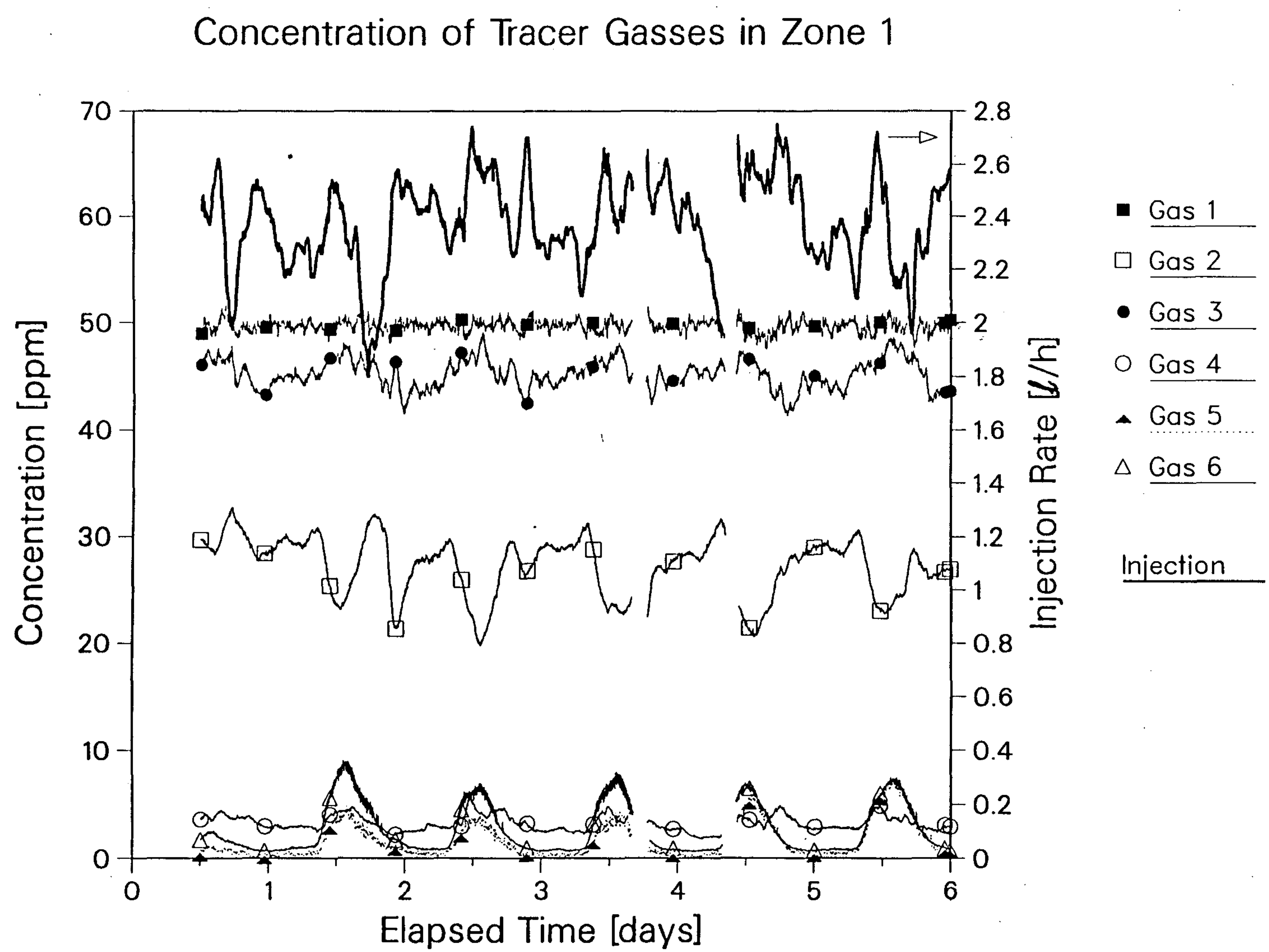

Figure 2b: Shows concentrations of all gasses in zone 1.

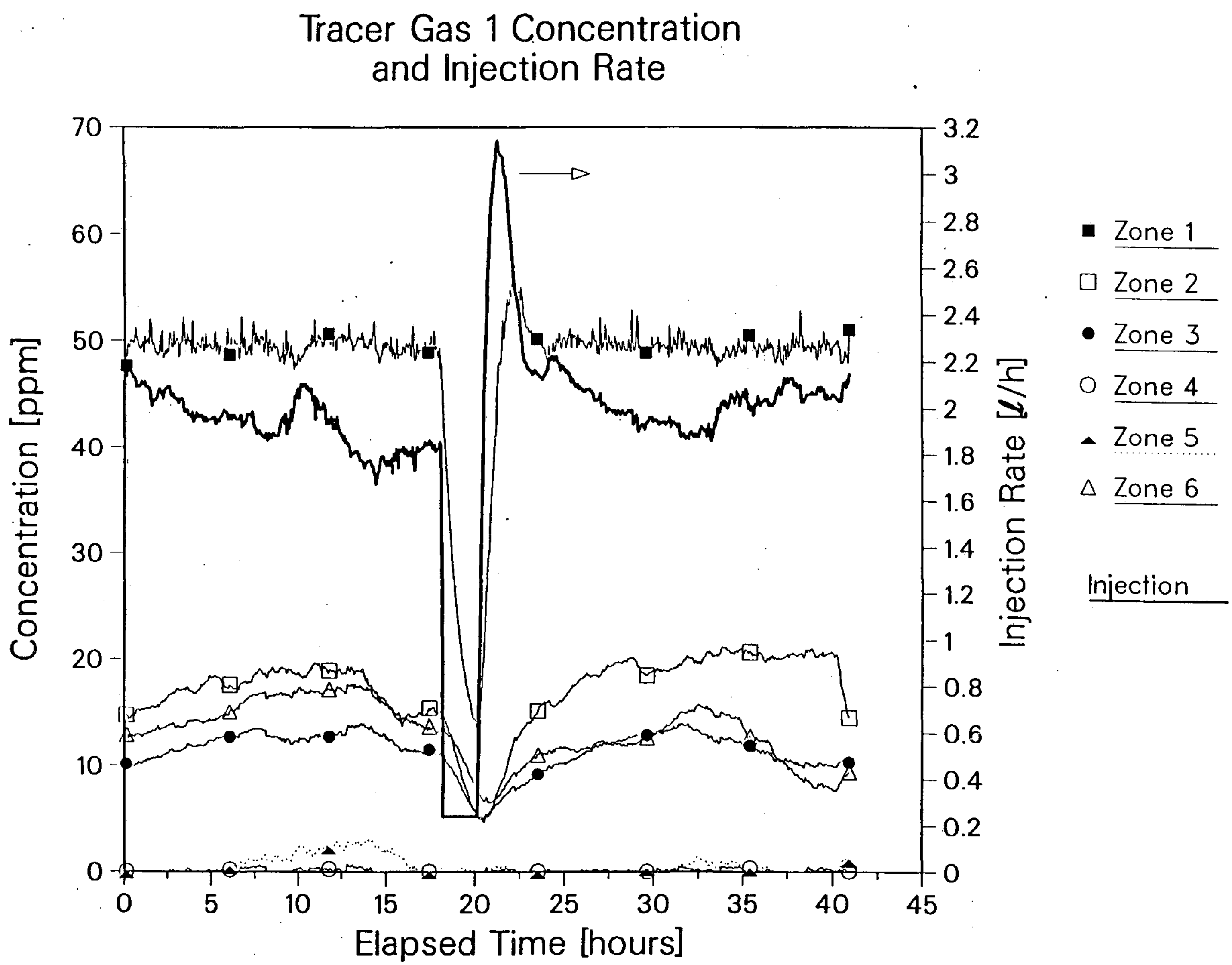

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Figure 3a: Shows concentrations of gas 4 in all zones.

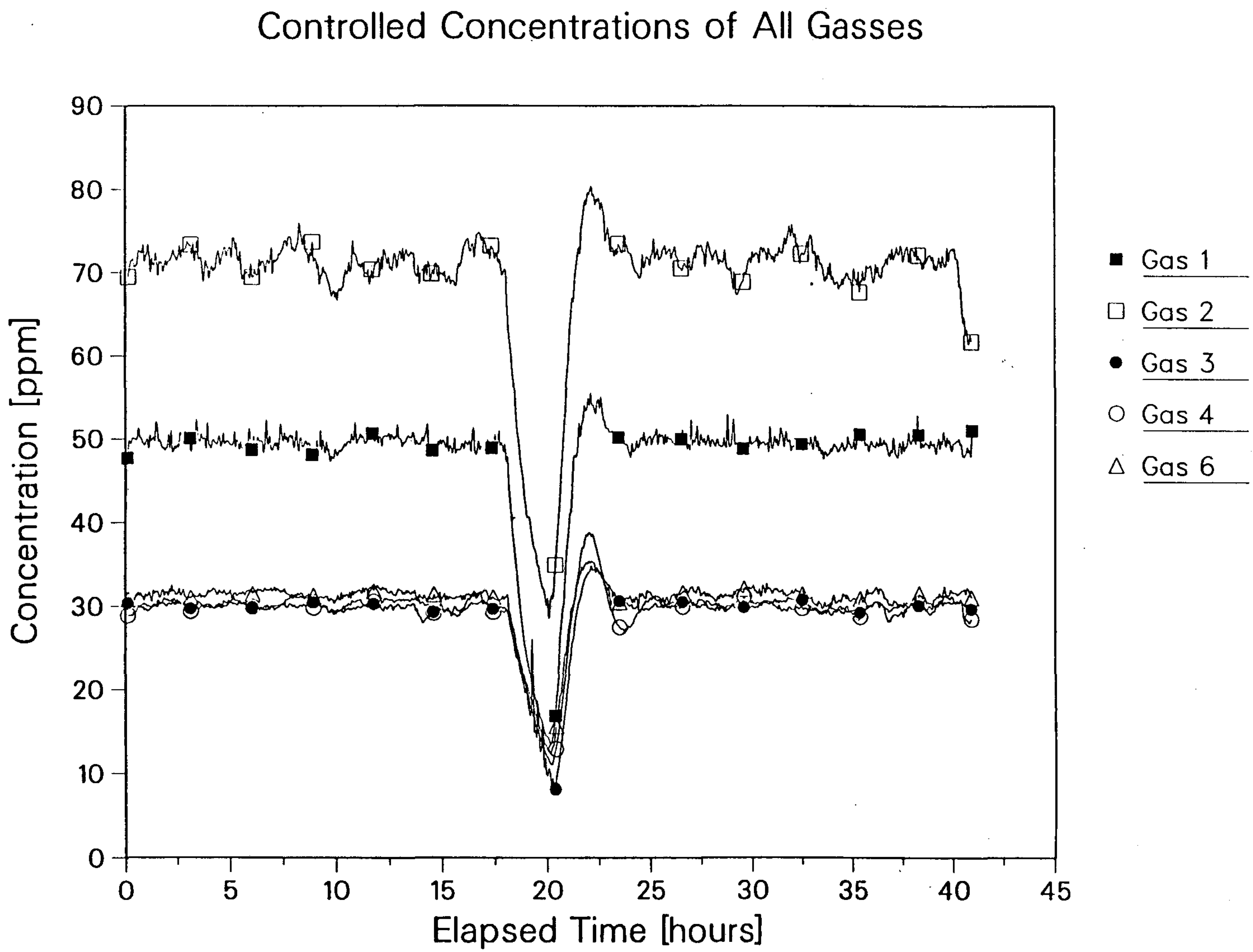

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Figure 3b: shows the concentration of the gas being injected into zones 1-4 and 6.

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