Evaluation of Leakage from a Metal Machining Center Using Tracer Gas Methods—A Case Study

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ABSTRACT

Engineering controls for reducing worker exposure to metalworking fluids were evaluated for a machining center during face milling operations. An enclosure was built around a vertical metal machining center (LANCER™ model 1000, Cincinnati Milacron) with an attached ventilation system consisting of a 25-cm diameter duct, a fan, and an air-cleaning filter. The evaluation method included sulfur hexafluoride (SF_6) tracer gas to determine the ventilation system's flow rate and capture efficiency, a respirable aerosol monitor (RAM) to identify aerosol leak locations around the enclosure, and smoke tubes and a velometer to evaluate air movement around the outside of the enclosure. Results of the tracer gas evaluation indicated that the control system was approximately 98% efficient at capturing tracer gas released near the spindle of the machining center. This result was not significantly different from 100% efficiency ($p = 0.2$). The measured SF_6 concentration, when released directly into the duct, had a relative standard deviation of 2.2%. When SF_6 was released at the spindle, the concentration had a significantly higher relative standard deviation of 7.8% ($p = 0.016$). This increased variability may be due to cyclic leakage through a small gap between the upper and lower portion of the enclosure. Leakage was observed, using smoke tubes, a velometer, and an aerosol photometer. The tool and fluid motion combined to induce a periodic airflow in and out of the enclosure. These results suggest that tracer gas methods could be used to evaluate enclosure efficiency. However, aerosol instrumentation, such as optical particle counters or aerosol photometers, should also be used to locate leakage from enclosures.

INTRODUCTION

Because of adverse health effects associated with worker exposure to components of metalworking fluids, including dermatitis,[(1)] respiratory disease,[(2)] and asthma,[(3)] worker exposure to airborne metalworking fluid mist needs to be controlled. Automated machining centers can be enclosed by the machine manufacturer and vented to an air cleaner to control the metalworking fluid mists that are generated by the machining operation. The ability of ventilated enclosures to prevent the emission of metalworking fluid mists into the workplace can be evaluated by tracer gas methods.

This paper presents the findings of a tracer gas evaluation of an enclosure for an automated machining center during face milling operations. This evaluation was conducted based upon a successful tracer gas method used to evaluate engineering controls for asphalt pavers by the National Institute for Occupational Safety and Health (NIOSH).[(4)] A similar tracer gas method is an integral part of an American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) National Voluntary Consensus Standard for testing the performance of laboratory fume hoods (ANSI/ASHRAE 110-1985).[(5)]

METHODOLOGY

Engineering controls for reducing worker exposure to metalworking fluids were evaluated for a machining center during face milling operations at the General Motors Technical Center in Warren, Michigan. An enclosure was built around a vertical metal machining center (LANCER™, Cincinnati Milacron, Cincinnati Ohio), and a ventilation system was added consisting of a 25-cm diameter duct, a direct-drive, backward-inclined centrifugal fan, and a three-stage filtration system, which included a high-efficiency, particulate air (HEPA) filter.

The ventilation system had two elbows between the machining enclosure and the air filter. In addition, there were two elbows downstream of the air cleaner. A diagram of the metal machining center and its major components is shown in Figure 1.

The evaluation method utilized a tracer gas evaluation and an aerosol photometer (RAM-1, MIE Inc., Bedford, MA), a velometer, and smoke tubes to identify aerosol leakage and air movement near the enclosure. A pitot tube traverse was used as a back-up method to evaluate airflow within the duct.

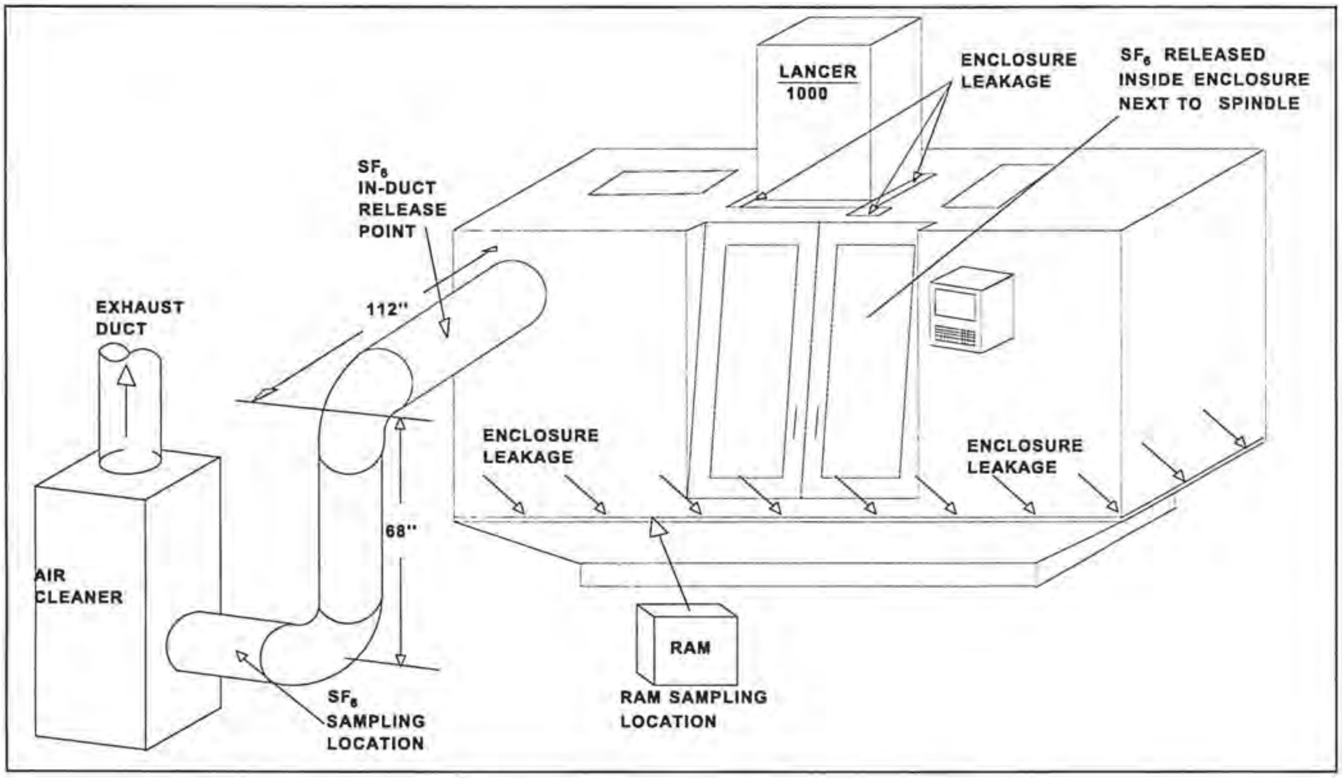

Figure 1. Schematic of machining center and ventilation system

Sulfur Hexafluoride Tracer Gas Test

The tracer gas test was used to (1) calculate the total exhaust flow rate of the ventilation system and (2) evaluate the system's effectiveness in capturing and controlling a surrogate contaminant. SF_6 was used as the surrogate contaminant. To do this, SF_6 was released at a known, controlled rate into the ventilation duct and into the enclosure. A mass flow controller (FTS4, MKS , Walpole, MA) was used to regulate the SF_6 flow rate. The concentration of SF_6 was measured with a photo-acoustic infrared detector (Multi Gas Monitor Type 1302, Bruel and Kjaer, Naerum, Denmark). The concentration was measured when the SF_6 was released into the duct and into the enclosure near the spindle. The SF_6 detector was calibrated prior to testing, using standard concentrations of SF_6. The mass-flow controller was calibrated using a bubble meter and timer.

To measure the airflow and concentration at 100% capture efficiency, 1,500 cm^3/minute of pure SF_6 was released into the ventilation system. The SF_6 flowed through the flow controller and out of a 1/4-inch-diameter discharge tube placed into the duct near the connection to the enclosure. The SF_6 concentration was measured 14 duct diameters and 2 elbows downstream from where the duct connected to the machining center enclosure (Figure 1). The instrument's sampling probe was placed through a 1/4-inch-diameter hole in the exhaust duct, perpendicular to the airflow. The 1/8-inch-diameter tubing was connected to the sampling probe and to the detector. To obtain the enclosure's efficiency, the SF_6 gas was released through the 1/4-inch-diameter discharge tubes into the enclosure near the spindle.

The 1,500 cm^3/minute of pure SF_6 was chosen in order to minimize the effects of SF_6 solubility in the metalworking fluid. SF_6 is slightly soluble in water (approximately 5.4 cm^3 SF_6/ kg H_2O at 21°C).[6] During the testing, a semi-synthetic metalworking fluid was applied at a flow rate of 18 liters per minute (lpm). Based on that flow rate, the fluid could absorb as much as 0.097 lpm of SF_6, or approximately 0.6%.

The sampling location was chosen to ensure adequate mixing of tracer gas in the duct. Hampl et al. experimentally evaluated the effect of sampling location upon SF_6 dispersion in ventilation systems.[7] In Hampl's work, the SF_6 concentration was measured at different locations in the duct, and the coefficient of variation (CV, the standard deviation divided by the mean expressed as a percent) for these measurements was used as a measure of the dispersion of SF_6 throughout the duct. When SF_6 was released from a single point or from four points in a straight run of duct, 25-50 duct diameters were needed to keep the CV below 5%. Apparently, the number of release points did not affect dispersion throughout the duct. When the sampling and release locations were separated by 2 elbows and 10 duct diameters, the CV was under 5%.

The exhaust volume was computed as follows:

$$Q_{(exh)} = (Q_{(SF6)} / C^*_{(SF6)}) \text{ X } 10^6 \qquad (1)$$

Where:

$Q_{(exh)}$ = airflow through the ventilation system (cubic feet/minute)

$Q_{(SF6)}$ = flow rate of SF_6 (cubic feet/minute), and

$C^*_{(SF6)}$ = concentration of SF_6 (parts per million) detected in the exhaust duct when SF_6 was released in exhaust duct.

Sufficient time was allowed between tests for the background readings near the SF_6 detector to drop below 0.1 ppm. Enclosure efficiency, η, was computed from $C^*_{(SF6)}$ and $C_{(SF6)}$, the concentration of SF_6 measured in the duct when SF_6 was released near the tool's spindle:

$$\eta = (C_{(SF6)} / C^*_{(SF6)}) \text{ X } 100 \qquad (2)$$

Background SF_6 concentration was periodically monitored to determine whether any SF_6 had accumulated in the test area.

Leakage Identification and Enclosure Flow Rates

The RAM continuously sampled the air from the gap between the upper and lower portions of the metal machining center enclosure. The RAM operated on the 0-2 mg/m^3 range and at a time constant of 2 seconds. The RAM measures the quantity of light scattered by the entire aerosol cloud and provides a measure of relative concentration based upon concentration and the aerosol's optical properties. The analog output of this instrument was recorded using a data logger (Ranger II, Rustrack, East Greenwich, RI).

Smoke tubes were used to qualitatively evaluate airflow near suspected leaks from the enclosure. A velometer (Velocicalc, TSI, Inc., St. Paul, MN) was also used to quantify the air movement near the identified leaks. Smoke tubes were used to evaluate air movement within the enclosure. Airflow within the duct was evaluated using the previously described SF_6 method and a pitot tube traverse. The 10-point, equal area pitot tube traverse was conducted in the duct upstream of the air cleaner to determine the average duct velocity and flow rate.[8]

RESULTS

The tracer gas concentration measured downstream when the SF_6 was released at the spindle and in the duct are reported in Table 1. Based upon the results of a pooled t-test for heterogeneous variances, the concentrations measured when SF_6 was released at the spindle and in the duct did not differ significantly ($p=0.2$). Within experimental error, the enclosure captured all of the tracer gas released at the spindle. However, the standard deviations were significantly different ($p= 0.016$). The increased standard deviation when SF_6 was released at the spindle is surprising. If the enclosure was working properly, it should have dampened fluctuations in the SF_6 concentrations measured when released inside the enclosure. Airflow through the duct, based upon SF_6 measurements, was determined to be approximately 540 cfm.

Table 1. Summary Statistics for SF_6 Concentration Measurements

	SF_6 Released In Duct	SF_6 Released In Enclosure
Mean (ppm)	98.1	96.3
Standard Deviation (ppm)	2.3	7.5
Number of Measurements	15	13

The pitot tube traverse indicated that the airflow in the duct was approximately 521 cfm based upon an average velocity pressure of 0.057 inches water gauge. This value is consistent with the tracer gas results. Smoke tubes were instrumental in identifying leakage near the base of the metal machining center. There was a 0.25 inch gap between the top and bottom of the enclosure around the entire perimeter as shown in Figure 1. Leakage from the enclosure was visualized with smoke. The air motion induced by the metal removal spray generated by face milling appeared to cause the smoke to periodically flow out of the enclosure. Velometer measurements taken at the leak from the enclosure perimeter fluctuated between 200 and 600 feet per minute. Once the leakage source was identified, it was possible to quantify the leakage by using the velometer, taking physical measurements, and conducting air sampling with the RAM.

As depicted in Figure 2, aerosol photometer measurements showed that leakage occurred near a small gap between the upper and lower portions of the enclosure. The higher response depicted by a broken line was measured inside the duct during milling, and the solid line depicts the readings taken near leakage at the base of the enclosure. The solid line is cyclical and moves between 0 and 0.15 volts. These peak concentrations occurred when the spray from the face mill was directed toward the RAM's sampling location. Apparently, the airflow induced by the motion of the face mill was blowing mist out of the enclosure.

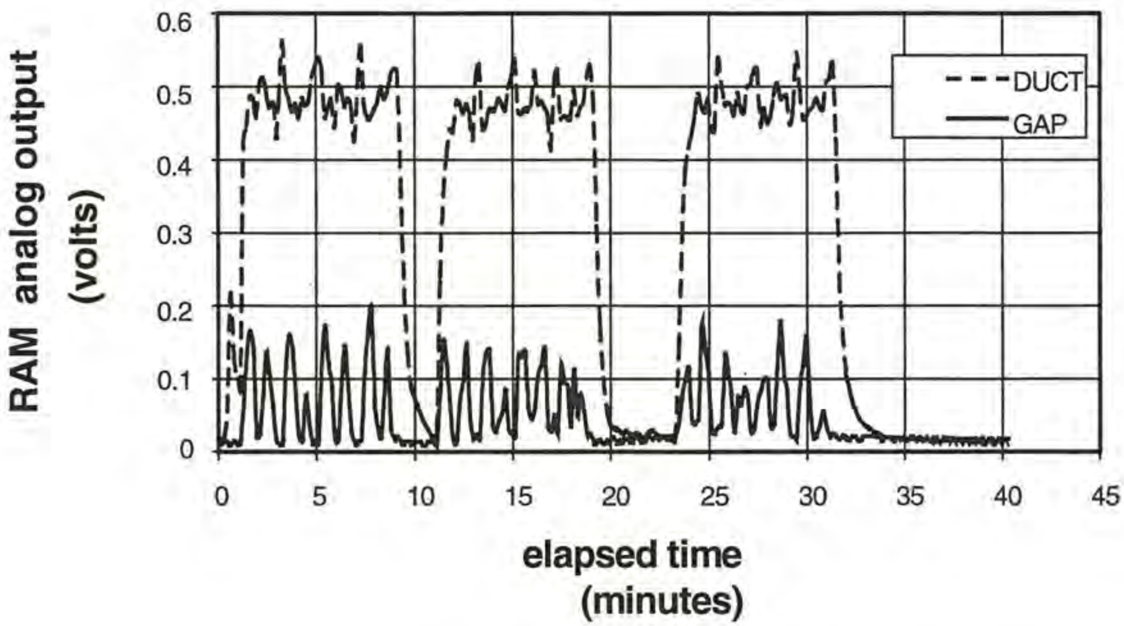

Figure 2. Aerosol photometer measurements of ventilation duct concentration and enclosure leakage

DISCUSSION AND RECOMMENDATIONS

The cyclic nature of the mist emissions can cause increased variability in the measured tracer gas concentration. By sampling a periodic phenomenon with instantaneous readings, the variability and bias of the measured concentrations may increase. In this technique, the SF_6 concentration was measured at approximately 30-40 second intervals. Examination of the aerosol photometer measurements in Figure 2 indicates that mist leakage had a period of about 1 minute. Because the frequency of SF_6 measurement was less than twice the frequency of mist leakage, the average SF_6 measurements may be biased.[9, 10] The issues of bias and increased variability could be avoided by collecting air samples in a gas bag over several complete production cycles.

The ability of this tracer gas method, as conducted, to identify leakage is limited by the precision of the tracer gas concentration measurement for the gas released in the duct and in the enclosure. A pooled t-test was used to evaluate whether significant leakage occurred. Figure 3 shows the probability that this test would determine significant leakage when leakage is occurring. The computation assumes 10 independent measurements for each location, a relative standard deviation of 2.5% for each location, and a normal distribution. Figure 3 indicates that the tracer gas test as conducted can be used to ensure that leakage is no greater than approximately 7-8%. There may be a need to improve the precision of the tracer gas test by gathering more data or by quantifying the percentage of escaping emissions (leakage) rather than captured emissions. Quantifying leakage could be done by placing the enclosed machining center in a ventilated room and measuring tracer gas in the air that is exhausted from the room.

Capture efficiency at various airflow rates should be evaluated by machine manufacturers before their equipment is sold. The manufacturer should simulate machining operations with metalworking fluid in order to generate induced airflow. An aerosol photometer should be used to identify mist leakage, and tracer gas methods should be used to evaluate enclosure efficiency. A manufacturer's testing area with provisions for adequately mixing and variable airflow is needed. This tracer gas method is a robust method that could serve the metalworking industry well. Additional testing is needed.

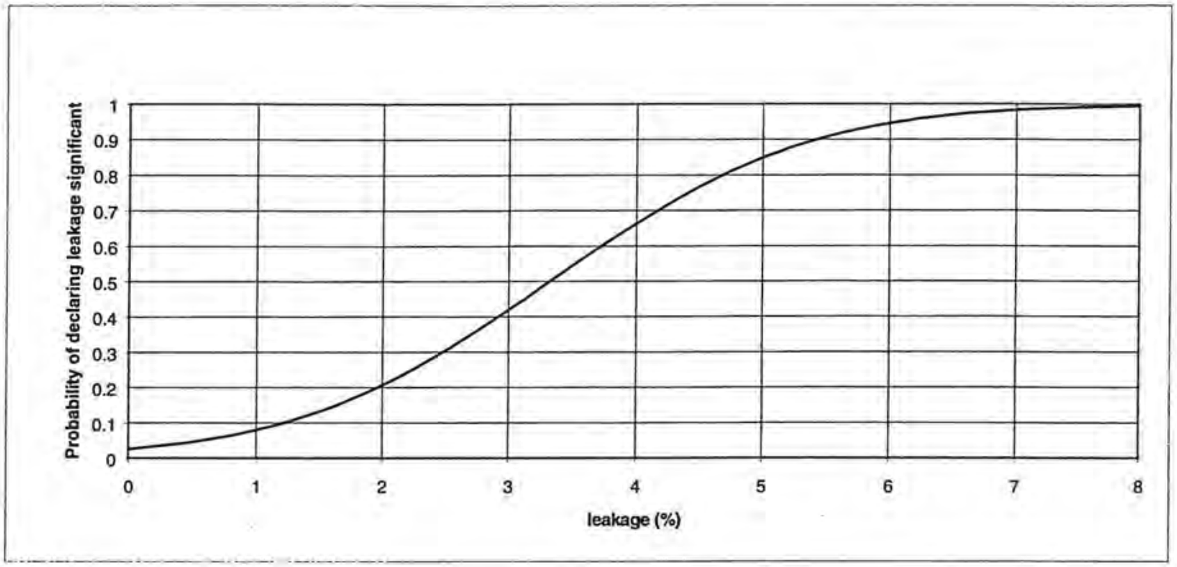

Figure 3. Probability of detecting a statistically significant leakage rate with the tracer gas technique used in this study as a function of leakage rate.

DISCLAIMER

Mention of any company or products does not constitute endorsement by the Centers for Disease Control and Prevention (CDC), National Institute for Occupational Safety and Health (NIOSH).

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The reader will notice a variety of nomenclature differences among authors when referring to these fluids which were the subject of the Symposium and of this volume. Indeed, even the Symposium title reflected some of this variation: "*Metalworking* Fluids Symposium II," and "The Industrial Metalworking Environment: Assessment and Control of *Metal Removal* Fluids." Lest we add to the confusion, our use of the term *metalworking* in the title "Metalworking Fluids Symposium II" was a conscious decision based on nothing more than to maintain continuity with the title from the first Symposium. It was for that reason that "Assessment and Control of Metal Removal Fluids" was added in recognition of, and to call attention to the fact that the vast majority of research and data to date has been generated on a subset or class of metalworking fluids known as **metal removal fluids**. In addition to metal removal fluids, the very general term 'metalworking' fluids also encompasses the large and general classes of *metal protecting* fluids, *metal forming* fluids, and *metal treating* fluids. Besides functional differences between metalworking fluid classes, there are substantial compositional differences both between and within classes. So while it is somewhat sloppy though quite common and generally harmless to use generic terms such as metalworking fluids, or machining fluids, or coolants, the reader should be well aware of these important distinctions and that in virtually all instances where there is a connection with purported health effects, the person is really referring to that subclass of metalworking fluids known as *metal removal fluids*.

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