A QUANTITATIVE METHOD FOR OPTIMIZED PLACEMENT OF CONTINUOUS AIR MONITORS

Jeffrey J. Whicker,* John C. Rodgers,* and John S. Moxley†

Abstract—**Alarming continuous air monitors (CAMs) are a critical component for worker protection in facilities that handle large amounts of hazardous materials. In nuclear facilities, continuous air monitors alarm when levels of airborne radioactive materials exceed alarm thresholds, thus prompting workers to exit the room to reduce inhalation exposures. To maintain a high level of worker protection, continuous air monitors are required to detect radioactive aerosol clouds quickly and with good sensitivity. This requires that there are sufficient numbers of continuous air monitors in a room and that they are well positioned. Yet there are no published methodologies to quantitatively determine the optimal number and placement of continuous air monitors in a room. The goal of this study was to develop and test an approach to quantitatively determine optimal number and placement of continuous air monitors in a room. The method we have developed uses tracer aerosol releases (to simulate accidental releases) and the measurement of the temporal and spatial aspects of the dispersion of the tracer aerosol through the room. The aerosol dispersion data is then analyzed to optimize continuous air monitor utilization based on simulated worker exposure. This method was tested in a room within a Department of Energy operated plutonium facility at the Savannah River Site in South Carolina, U.S. Results from this study show that the value of quantitative airflow and aerosol dispersion studies is significant and that worker protection can be significantly improved while balancing the costs associated with CAM programs.**

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INTRODUCTION

THE GOAL of alarming continuous air monitors (CAMs) is to reduce inhalation exposures to radioactive materials by alerting workers to accidental airborne releases into the room, and properly utilized CAMs can provide a high level of worker protection. Because of the critical role of CAMs in providing workers an early warning of an accidental airborne release, they are essential in many facilities that contain large quantities of dispersible materials that are hazardous. In fact, regulators for Department of Energy (DOE) facilities that contain large amounts of radioactive materials require CAMs in situations where the inhalation hazard is sufficiently high (U.S. DOE 1999a). However, it is not solely sufficient to have CAMs in these workrooms, but they must also perform a continuous monitoring and alarm function at a high level to provide adequate protection to workers. Specifically, CAMs should provide for sensitive and fast detection of accidental releases.

A critical factor in determining the performance (sensitivity and timeliness of alarms) is the number and placement of CAMs in a monitored room (Whicker et al. 1997). Crites (1994) demonstrated, based on a review of detailed records of radiological air monitoring and CAM alarm incidents, that CAMs in DOE plutonium facilities alarmed less than 33% of the time when plutonium aerosol releases into monitored rooms exceeded 500 DAC-h (hours), despite instrument sensitivities that were generally in the 20 DAC-h range. Follow-up studies to the Crites (1994) study showed that significant dilution of the released material can occur before the aerosol cloud arrives at typical CAM locations (especially for short-duration "puff" releases, which are the most common type), and the observed dilution between the CAM locations and the release locations largely explained the low CAM detection percentage (Whicker 1993; Whicker et al. 1997). In addition to dilution considerations in CAM performance, Whicker et al. (1997) showed that worker exposure can occur quickly and that in order for CAMs to effectively reduce exposures, they must be positioned in order to detect the releases rapidly.

Studies to help with the determination of the number and placement of CAMs in rooms can be categorized as either "qualitative" or "quantitative" (Hickey et al. 1993). Qualitative studies include commonly used "smoke" studies where a smoke or powder is released

* Los Alamos National Laboratory, Health Physics Measurements Group, Mail Stop G761, Los Alamos, NM 87545. † Savannah River Site, Radiological Technology Group, 707–48B, Aiken, SC 29808.

For correspondence or reprints contact: J. J. Whicker, Los Alamos National Laboratory, Health Physics Measurements Group, Mail Stop G761, Los Alamos, NM 87545, or email at jjwhicker@lanl.gov.

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into a room from representative locations where accidental releases might occur. The movement of the smoke is observed and then traced onto a room map to indicate its direction. The CAM placement strategy is then to find, if possible, locations that are generally "downwind" of the release location(s). However, these qualitative studies may not reveal preferred CAM locations due to the complexities of room airflow patterns. Further, qualitative smoke studies provide no direct measurement of 1) the time required for a released aerosol to travel to a CAM location, or 2) the amount of aerosol dilution that occurs as the released material mixes into the clean room air. In contrast, quantitative studies, such as studies with sonic anemometers and tracer releases, provide direct measurement of transport rates and dilution that can be used to evaluate CAM placement.

Quantitative studies have been performed to aid in the evaluation of CAM placement through measurement of airflow characteristics (direction, velocity, turbulence) and others have been performed using aerosol or gas tracers. Regarding measurement of airflow characteristics, recent advances in instrumentation have allowed detailed studies of airflow characteristics in rooms (Wasiolek et al. 1999). For example, Whicker et al. (2000a) measured airflow velocities and turbulence intensities in a nuclear facility and found velocities ranging up to 0.42 m s^{-1} and turbulence intensities in the 14–57% range. Others have found similar values in other mechanically ventilated rooms (Hanzawa et al. 1987; Awbi 1991; Heber and Boon 1993). Further, airflow characteristics are dependent on ventilation rate and room layout (Whicker et al. 2002). Studies to directly measure aerosol dilution and transport rates using tracer aerosols have also been done. Specifically, tracer studies of aerosol dispersion in plutonium facilities have demonstrated that there can be significant dilution of aerosol or gas between the release location and the sampling locations (Brunskill and Holt 1967; Scripsick et al. 1979; Mishima et al. 1988; Alvarez et al. 1994; Flynn et al. 1996; Drescher et al. 1997; Whicker et al. 1997). In addition to dilution, transport times for the travel of a released material to a monitoring location have been measured in nuclear facilities (Langer 1987; Whicker et al. 1997), and these studies showed that good placement of samplers also led to faster detection of the releases. Whicker et al. (1997) showed that fast detection of accidental releases was critical to exposure reduction because worker exposures can occur very quickly (i.e., over 80% of the exposure is received in the first few minutes). Therefore, improper placement of CAMs can reduce the ability of a CAM to adequately monitor and provide sensitive and fast warnings to the workers.

While positioning of CAMs relative to release locations is critical for providing adequate protection of workers, optimization of the number and placement is a further, but important, consideration when determining CAM utilization (number and placement of CAMs in a room). Optimization implies that an evaluation of the costs and benefits of possible CAM placement strategies be done. In fact, guidance within the Department of Energy (DOE 1999b) not only emphasizes the critical importance of placement of CAMs, it also requires that the CAMs be optimally utilized (i.e., that the maximum benefit be attained for the number of CAMs used). This is important because in many rooms with hazardous materials, there are many possible release locations. This fact, combined with the high cost of each CAM, make it prohibitively expensive to attempt to locate a CAM immediately downwind from each possible release location.

Limited research has been published on optimization of CAM use in nuclear facilities. Merwin et al. (1989) show an example of performing optimization techniques in evaluation of CAM use in accordance with the International Commission on Radiological Protection (ICRP) publication No. 37 (1983). In this evaluation, Merwin et al. (1989) used quantitative data from Scripsick et al. (1979) to calculate an average committed effective dose equivalent (CEDE) per release. Using this dose per release and a selected value for dollars per person-Seivert (i.e., $100,000 per person-Seivert), the number of CAMs required can be determined based on the expected number of releases per year. However, as pointed out in the Merwin et al. (1989) paper, the Scripsick et al. (1979) study was done using 15-min releases and 30-min average concentrations. However, such protracted release and averaging times are not typical of releases in plutonium facilities (Mishima et al. 1988; McAtee 1990; Whicker 1993). Further, Whicker et al. (1997) showed that use of dilution measures to estimate worker exposures using concentrations that are averaged over long-time periods could result in underestimating worker exposure by several orders-of-magnitude because the measurements were not sufficiently time-resolved to accurately evaluate the time-dependent nature of worker exposure. Evaluation of CAM optimization using the method outlined in Merwin et al. (1989), but correcting the CEDE estimates per event by using more common "puff" release conditions, could significantly increase the number of CAMs required. Finally, Merwin et al. (1989) evaluated the optimized number of CAMs in a room, but they did not evaluate the critical nature of placement of the CAMs in a room. For example, results from Scripsick et al. (1979) and Whicker et al. (1997) suggest that one or two

well-placed CAMs could provide significantly better protection than more but less-optimally placed CAMs. Therefore, a comprehensive technique was needed to determine optimal utilization (number and placement) of CAMs using more realistic release scenarios.

The goal of this study was to develop a quantitative method for determination of the optimal number and placement of CAMs in a room using techniques that account for the time-dependent nature of worker dose and CAM response. This paper describes a unique quantitative method for optimizing CAM utilization that provides a balance between worker protection and number and placement of CAMs in a room. To illustrate the optimization method, we provide a step-by-step description of the measurement methods, results, and analysis for the optimization of CAM use inside a DOE-operated plutonium laboratory at the Savannah River Site (SRS) in South Carolina, U.S.

MATERIALS AND METHODS

In this section, the necessary steps and considerations for evaluation and optimization of CAM utilization are described. These steps include (1) select the room(s) for study; (2) establish release locations and conditions; (3) select potential sampling locations; and (4) determine optimized placement using the data analysis techniques outlined below. For each of these steps, an example is given that is based on a CAM placement evaluation and optimization study at the SRS.

Room selection

The first step in determining optimal CAM numbers and placement is to select the room(s) to study. The rooms that receive the greatest attention can be those with the greatest hazard to workers (i.e., more potential for releases and worker exposure). Although caution is advised because of complexity of airflow in rooms (Konecni et al. 2002), if a selected room is sufficiently similar in ventilation design and room layout, the selected room may be representative of other rooms in the facility (Whicker et al. 2002). When deciding on the representativeness of the room it is especially important to consider the location and design of the room air supply diffusers, room air exchange rates, and larger obstructions because of their large influence on room airflow (Awbi 1991; Buchanan et al. 1995; Haghighat et al. 1996).

For this case, a room designed for low-level plutonium chemistry was selected. The room was similar in size, layout, and ventilation design to other rooms in the facility. Fig. 1 is a schematic showing the significant features of the room. The supply air is introduced into the room through a series of diffusers along a ceiling strip that runs through the middle of the room. Room air is exhausted through chemical hoods. The room air exchange rate was estimated to be about 15 room air exchanges per hour (15 ACH). The room has a series of gloveboxes and chemical hoods on both sides of the aisle. In addition, there is a sink and a small computer workstation in the room. Historically, there has been one CAM monitoring location as is indicated in Fig. 1.

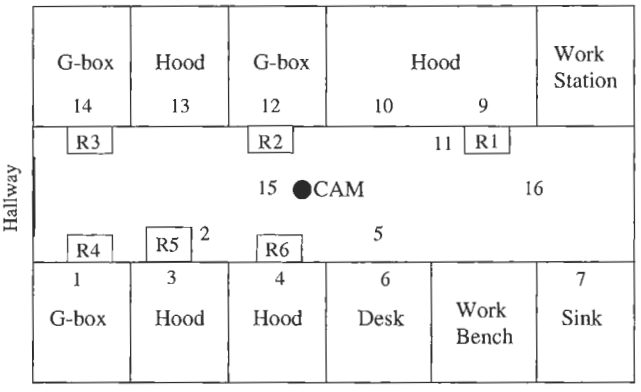

Fig. 1. Map of room where tracer aerosol study was performed with LPC sampling locations (1–16) and release locations (R1–R6). LPC number 15 is approximately at the same sampling location of the current CAM monitoring location as indicated by the shaded circle. The hallway is to the left of the room.

Select tracer release locations and conditions

After a room is selected, potential locations for tracer releases need to be determined. Locations in the room that have greater potential for a release are good candidates for tracer releases. The level of release potential may be evaluated using historical radiological release data or may be based on an evaluation of the risk of the job performed at a workstation (i.e., use of sharp tools, corrosive chemicals, pressurized systems, etc.). For larger rooms with numerous possible release locations, it may not be possible to select all locations for tracer releases. In these cases, a representative set of release locations might be determined. In addition to determining release locations, an appropriate tracer should be identified that has similar aerodynamic properties to material used in the room. For example, in rooms where tritium is worked with, aerosol tracer generators that produce significant numbers of large particles (i.e., aerodynamic diameters greater than 10 μm) may not be adequate tracers. Likewise, in rooms where larger particles of plutonium could be released (i.e., aerodynamic diameters greater than 10 μm), gas tracers such as sulfur hexaflouride (SF_6) gas may not be a suitable tracer. In one study, Vavassuer et al. (1986) suggests that gas is a valid tracer for airborne particles up to particle diameters

of around 2 μm. However, even larger particles such as those with aerodynamic diameters of 10 μm have settling velocities of 0.3 cm s^{-1}, which is at least one or two orders-of-magnitude lower than air velocities found in nuclear facilities (Whicker et al. 2000a). Further, these 10 μm particles have short relaxation times of 3×10^{-4} s (Hinds 1982), which indicates low inertial momentum at room airflow velocities. For gases (e.g., tritium), the mean rate of travel due to Brownian displacement (molecular diffusion) for a hydrogen molecule is about 2 cm s^{-1} (Hinds 1982; Konecni et al. 2000), which is still about an order-of-magnitude lower than average airflow rates in a nuclear facility as reported in Whicker et al. (2000a). Combined, these analyses suggest that material (both gas and particle) transport in mechanically ventilated rooms is dominated by room airflow, unless a large fraction of airborne particles are significantly greater than 10 μm. Of course, particles of greatest importance to determining dose are those respirable particles less than 10 μm, but collection of larger radioactive particles, which are substantially more radioactive than smaller particles, can substantially increase CAM sensitivity. It is also important to simulate the energy of the typical release. For example, aerosol released from a high velocity jet is likely to disperse through both the breathing zone of a collocated worker and a room differently compared to more passive releases (Kim and Flynn 1992; Whicker 1993).

For this study, we were most interested in particles in the range of 0.1 μm up to about 10 μm as has been reported to be the size range of airborne plutonium particles (Dorrian and Bailey 1995). Therefore, we used an aerosol generator (Model 3079 Atomizer, TSI Incorporated, 500 Cardigan Road, P.O. Box 64394, St. Paul, MN 55164-0394) that generates polydisperse particles with a size range of 0.01 to 2 μm. The concentration produced was up to 10^8 particles per cubic centimeter and was sufficient for our laser particle counters (discussed in the next section) to measure above background aerosol concentrations. The aerosol exited the nozzle at an estimated velocity of about 10 cm s^{-1} and the aerosol was quickly assimilated into the local airflow patterns. Generated particles were Di-Ethyl-Hexyl-Sebacat (DEHS) oil droplets that are nontoxic and evaporate very slowly (a 0.3 μm particle has a typical lifetime of 4 h).

Locations for the tracer releases in the SRS laboratory were identified by room operations personnel and were based on most probable release scenarios (Fig. 1). Tracer releases at glovebox workstations were done to simulate a glovebox glove failure and were conducted about 30 cm in front of the glovebox face and at a height of the gloves. Tracer releases in front of chemical hoods were conducted near the floor to simulate a dropped sample that breaks on the floor and disperses the material into the air. Releases simulated "puff" type releases and were 60 s long. Three releases were performed at each of the six release locations (total of 18 releases) to assess statistical variability. Release probabilities at each of the tested release locations were assumed to be equal, but weighted averages can be used in the analysis if some release locations are a greater hazard than others in the room.

Select sampling locations and instrumentation

To determine the airborne tracer dispersion patterns in a room in time and space, measurements of tracer concentration over time must be made at numerous locations within the room. For this, the instrumentation selected should allow for rapid measurement of the tracer and should be capable of simultaneous measurements at numerous locations. Some researchers have collected grab samples (over time and at numerous locations) using syringes to sample the air for the tracer (Vavasseur et al. 1986; Langer 1987; Newton et al. 1993). Others have used networked real-time particle counters that are distributed through a room to sample the air remotely (Whicker 1997; Whicker et al. 2002).

The instrumentation used in the SRS laboratory is based on a system that was developed primarily for the clean room industry but has been used in past evaluations of CAM placement and indoor aerosol dispersion (Whicker et al. 1997; Whicker et al. 2002). This system employs Laser Particle Counters (LPCs) (Model 7550, Particle Measuring Systems, 5475 Airport Boulevard, Boulder, CO 80301). Vacuum pumps draw air into the sampling volume of the LPCs that contains a laser beam that passes through it. As airborne particles pass through the sampling volume, they travel through the beam and scatter the laser light. The scattered light impinges on photodiodes that then convert the light to electrical pulses that are counted. In this way, the number of particles per cubic meter (particle concentration) is determined. Sampling interval times can be preselected with the most frequent interval of once every 10 s, which was the time interval used in this study. Up to 16 LPCs can be networked into a single multiplexer (Model 3701, TSI Incorporated, 500 Cardigan Road, P.O. Box 64394, St. Paul, MN 55164-0394). Fig. 2 shows an example of the concentration time profile measured by a single LPC.

Selection of the tracer sampling locations requires consideration of release locations, airflow patterns (if known), locations of workstations and work patterns, practical considerations such as convenience and assessability, and current CAM locations (for evaluation of current placement and comparison to other potential sampling locations). Selection of the tracer sampling

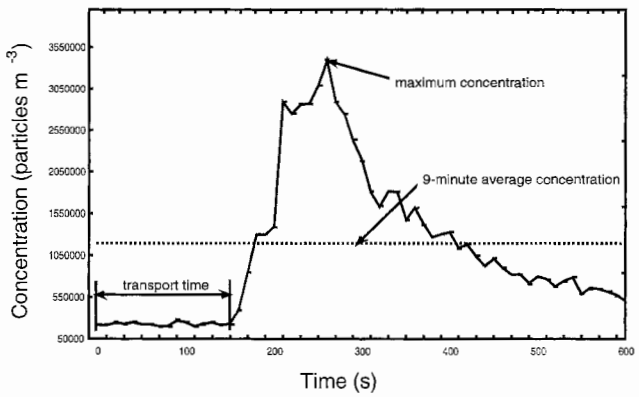

Fig. 2. Metrics used in evaluation of CAM placement.

locations is important because these represent potential locations of CAMs in the room. Gilbert (1987) provides helpful guidance for determining a statistically-based sampling strategy based on the particulars for a given application.

We used a modified systematic sampling approach in selecting the locations of the LPCs as shown in Fig. 1. In this case, sampling locations were placed on one of three transects running from one end of the room to the other. Two transects ran down the sides of the room and LPC samplers were placed at each workstation (LPCs 1–7; LPCs 9–12) and one transect was down the middle of the room (LPCs 12–16). LPC 15 was located within 1 m of the current CAM monitoring location. One LPC (LPC 8) was used to monitor the "breathing zone (BZ)" concentration near the release location. LPC 8 sampler was placed about 30 cm up and behind the aerosol generator and was used as an estimate of the breathing zone concentration of a worker who caused and was next to the initial aerosol release. Having LPCs throughout the room and at the release site provides valuable insight into the interplay between worker exposure and CAM performance.

Finally, measurements of room airflow velocities, direction, and turbulence were made in breathing zones at 20 different workstations in the room using a sonic anemometer (Model CSAT, Campbell Scientific, 815 West 1800 North, Logan, UT 84321-1784) as described in Wasiolek et al. (1999). The density of these point measurements was not sufficient to fully determine the complex airflow patterns in the room, but measurements of velocity and turbulence provide valuable information on the mixing rates in the room.

Data analysis

Metrics should be established for use in evaluation of potential CAM position(s) that includes measures for fast and sensitive detection once an accidental release occurs. Fig. 2 shows the metrics that were directly measured. The transport time (TT) is generally defined as the time interval for the released material to travel from the release location to the sampling location. Specifically, TT was defined as the elapsed time from the start of the tracer aerosol release until the particle concentration exceeded three standard deviations of the average background concentration on two consecutive 10-s sampling intervals. This definition allowed for consistent identification of tracer particles above the natural fluctuations in the background concentrations of airborne particles. The maximum concentration was defined as the highest 10-s concentration of the tracer measured during the run, and the average concentration was defined as the tracer concentration measurements averaged over a 9-min interval (until the particle concentrations in the room were back down to background levels). The 9-min average was also used to determine the Dilution Ratio ($DR_{9\text{-min}}$) and was calculated as the ratio of the 9-min average concentration at a given LPC location divided by the same breathing zone concentration measurement. In addition, a spatial analysis for both the transport time and the dilution ratio was done using a Kriging technique (Gilbert 1987).

Through an optimization process, the number and placement of CAMs can be determined by evaluating an achieved level of worker protection as a function of the number of CAMs in a room. For optimization, an appropriate metric needs to be selected that can be combined in a way that captures both the need for fast (short transport times) and sensitive (little dilution) detection. The exposure fraction (EF) is a derived measure that we propose (eqn 1), but others have also been suggested (McFarland et al. 1997):

$$EF(i,j) = \frac{\int_0^{AT(i)} C_{bz(j)}(dt)}{\int_0^{9\text{ min}} C_{bz(j)}(dt)}, \qquad (1)$$

where $C_{bz(j)}$ = tracer concentration in the breathing zone for the jth release location, and $AT(i)$ = alarm time for the first alarm triggered at monitoring location i following a tracer release. $AT(i)$ was less than 9 min for all releases.

The EF for each monitoring location i was averaged over the three tracer releases at each of the j release locations.

In evaluation of CAM placement, it can be useful to measure the amount of exposure "saved," rather than the amount received. Therefore, from eqn (1), we calculate

the fraction of the exposure saved (ES) for each release and arrangement of monitors:

$$ES(i, j) = 1 - EF(i, j). \quad (2)$$

The ES(i,j) is simply the fractional amount of dose saved given a monitor alarm at location i for a release at location j. For example, if the ES was 0.9, then a CAM is estimated to have the capability to save 90% of the collocated worker's exposure relative to if there were no CAM alarm.

As shown in eqns (1) and (2), the EF and ES for each release location j will vary depending on the alarm time for a given monitor at location i [AT(i)]. Specifically, the shorter the AT (fast and sensitive detection), the lower will be the fractional EF. Therefore, EF then provides a valuable metric that can be used for comparison of various arrangements of monitoring locations and was used for this study. Fortran codes were developed to process the large amount of data that are collected during the tracer studies and to determine the optimized CAM placement.

For the SRS evaluation, the mean EF for each LPC location (averaged over all releases) was calculated. Specifically, the time profile of the concentration in the "breathing zone" (C_{bz}) was measured for each release (using LPC 8), and the AT(i) for all of the LPCs was determined. The AT(i) was defined to be equal to the transport time (i.e., time period until the particle concentrations statistically exceed the background levels). Then using the measured $C_{bz(j)}$ and the AT(i), the EF(i,j) for each LPC monitoring location was calculated (eqn 1) as an average over the three releases at each release location (Fig. 1). Optimization of the placement strategies was done by first evaluating which single monitoring location i provided for the lowest EF (largest ES) when averaged over all release locations. Next, we evaluated which combination of two monitors would provide the lowest average EF over all releases, then we determined the lowest average EF from the best combination of three monitor locations, and so on. Statistical comparisons of the EF from different combinations of potential CAM locations were done using the nonparametric Wilcoxon Matched Pairs Test with a significance level of $p \leq 0.05$.

RESULTS

For the aerosol tracer release study in the plutonium laboratory at the SRS, means for the transport times, the $DR_{9\text{-min}}$, and the EF for each combination of release and sampling location are provided in Table 1. Using all of these measures, one can then make comparisons of relative levels of worker protection among various CAM utilization strategies regarding number and placement of air samplers and CAMs, as detailed below.

Table 1. Mean and one standard deviation of transport time, $DR_{9\text{-min}}$, and ES as averaged over all release locations. LPC number 8 is the BZ sampler and number 15 is the current CAM sampling location.

LPC	Mean transport time (s)	Mean $DR_{9\text{-min}}$	Mean EF
1	47 ± 24	1.17 ± 0.86	0.16 ± 0.16
2	34 ± 15	1.14 ± 0.66	0.09 ± 0.10
3	39 ± 16	0.96 ± 0.52	0.10 ± 0.08
4	41 ± 10	0.53 ± 0.31	0.13 ± 0.09
5	48 ± 21	0.44 ± 0.29	0.16 ± 0.12
6	62 ± 24	0.46 ± 0.47	0.20 ± 0.10
7	78 ± 56	0.36 ± 0.38	0.28 ± 0.29
8	23 ± 10	1.00 ± 0.0	0.04 ± 0.04
9	79 ± 69	0.36 ± 0.34	0.27 ± 0.31
10	48 ± 22	0.33 ± 0.26	0.16 ± 0.14
11	44 ± 21	0.81 ± 0.70	0.15 ± 0.14
12	40 ± 8	0.45 ± 0.27	0.12 ± 0.07
13	44 ± 21	0.68 ± 0.50	0.16 ± 0.14
14	47 ± 24	0.80 ± 0.57	0.17 ± 0.16
15	38 ± 10	0.65 ± 0.24	0.12 ± 0.09
16	38 ± 21	1.37 ± 1.08	0.12 ± 0.12

Fig. 3a shows mean TT measurements categorized by sampling location and Fig. 3b shows the spatial distribution of the mean TTs. The mean TTs ranged from 34 s to 79 s with a median of 44 s. The median TT for the current CAM location (LPC Location 15) was 38 s. The best individual locations for a CAM would be those with small mean TTs with little variation across release locations. Monitoring locations with consistently short transport times indicate that aerosols released from a wide variety of locations within the room will reach these locations rapidly. Spatially, the lowest mean transport times were toward the center and upper half of the room (closest to the hallway).

Regarding the amount of dilution that occurred during the tracer releases, the distributions of the $DR_{9\text{-min}}$ categorized by sampling location are shown in Fig. 4a. Means of the $DR_{9\text{-min}}$ ranged from 0.33 to 1.37 with a median of 0.67. The mean $DR_{9\text{-min}}$ for the current CAM location was 0.65 with a standard deviation of 0.24. The approximate spatial distribution of the mean $DR_{9\text{-min}}$ is shown in Fig. 4b. The dilution ratios are highest in the middle and upper end of the room, but in some cases exceed 1.0 (i.e., sampling locations 1 and 16), but the variation is quite large. The wide variation implies that these sampling locations would be relatively good for sensitive detection of releases from some locations and relatively insensitive to small releases from other release locations. The large variability also might indicate the need for additional CAMs to provide coverage for releases from other possible locations within the entire room.

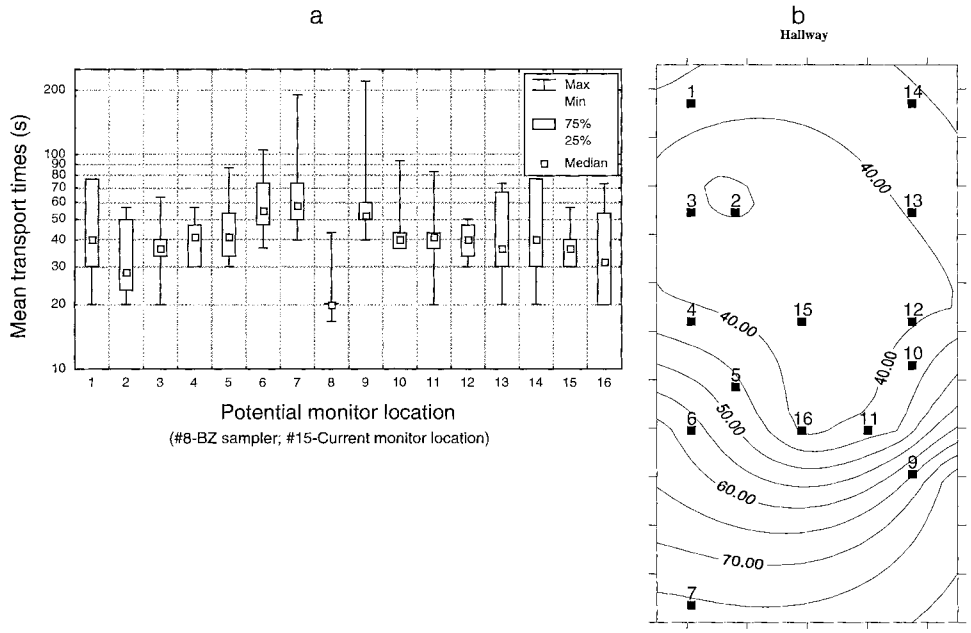

Fig. 3. Mean transport time distributions categorized by sampling locations (3a) and the estimated spatial distribution of mean transport times in the room (3b). Numbers (1–16) in Fig. 3b represent locations of LPCs as shown in Fig. 1.

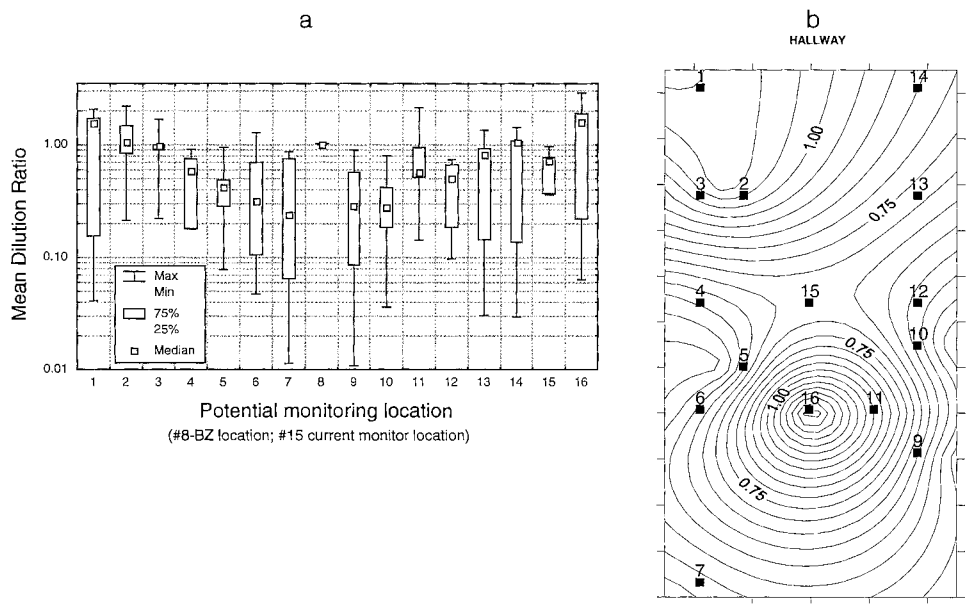

Fig. 4. Distributions of mean Dilution Ratios ($DR_{9\text{-}min}$) categorized by sampling locations (4a) and the estimated spatial distribution of the mean Dilution Ratios in the room (4b). Numbers (1–16) in Fig. 4b represent locations of LPCs as shown in Fig. 1.

Distributions of mean ES (eqn 2) are shown in Fig. 5a and the spatial distribution is shown in Fig. 5b. These data show that ES ranged from 0.72 to 0.92, with a median of 0.84. The ES for the current CAM locations was above the median at 0.88. These ES values are for each individual sampling location, but for CAM placement the best combination of locations should be determined for optimized placement. For this, all combinations of locations were evaluated using the EF metric (but could be done using the ES metric) and the best combinations determined. Table 2 contains the EF (eqn 1) for various numbers and potential sampling locations for CAMs, and Fig. 6 graphically shows the EF as a function of the number of CAMs. Using the EF values for different combinations of CAMs, we calculated

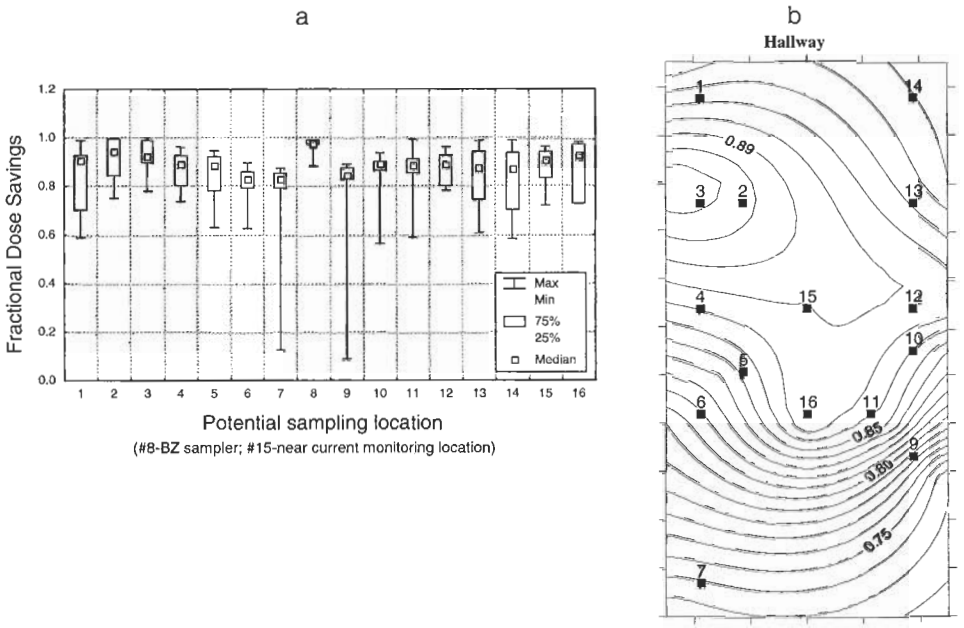

Fig. 5. Distributions of the fractional dose savings categorized by sampling locations (5a) and the estimated spatial distribution of mean transport times in the room (5b). Numbers (1–16) in Fig. 5b represent locations of LPCs as shown in Fig. 1.

the relative protection ($EF_{current}/EF_{1-5}$) as a function of the number of monitoring locations (1 CAM up to 5 or more CAMs) which is shown in Fig. 7. A statistical evaluation using the Wilcoxon Matched Pairs test showed a statistically significant lower EF for 3 CAMs, but no additional statistically significant improvement for more than three CAMs was found. This evaluation suggests that the current location provided an EF of almost 12%, and a statistically-determined optimal placement of 3 CAMs (locations 2, 10, and 16) provided an EF of 6%, or could improve performance by more than a factor of 2 relative to the current placement. Fig. 8 then shows locations of the optimized CAM placements.

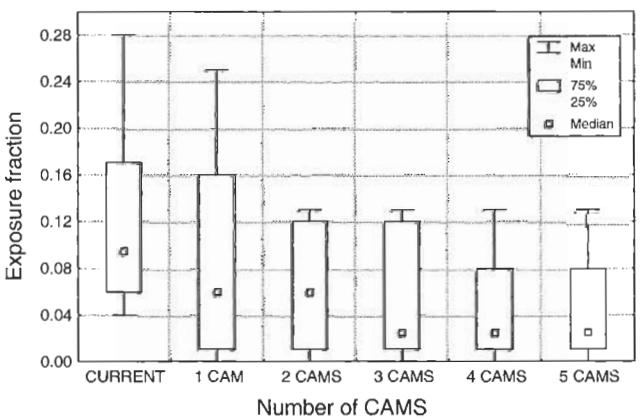

Fig. 6. Exposure fraction (EF) as a function of an increasing number of monitoring points. The EF for the current sampler is provided for comparison.

DISCUSSION

The proper number and placement of CAMs in a room are critical to protect workers to safe levels and is required by DOE regulations. Yet no quantitative methods existed to optimally utilize room CAMs. Therefore, a method to use quantitative measurements to optimize the number and placement of CAMs within workrooms was developed and shows that there is substantial opportunity for improving worker protection. While we did not perform an economic analysis, this study suggests that financial costs associated with CAM programs can be optimized through better CAM utilization and worker exposures lowered. For the example presented in this paper, a comparison of a single well-placed CAM (location 2) provided a mean EF of 0.09 whereas a more

Table 2. Comparisons of exposure fractions among possible CAM numbers and respective sampling locations. No improvement in exposure fraction was found with more than four sampling locations.

Possible number of CAMs	Sampling locations	Exposure fraction
1	2	0.09
2	2, 10	0.06
3	2, 10, 16	0.05
4	2, 5, 10, 16	0.04
Current placement	15	0.12

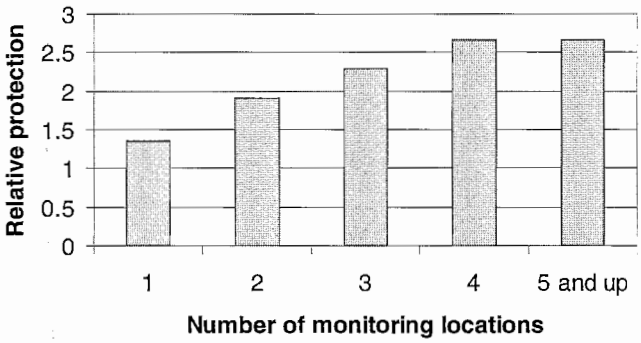

Fig. 7. The relative protection (EF current/EF 1–5) as a function of the number of CAMs. This calculation is based on average EF.

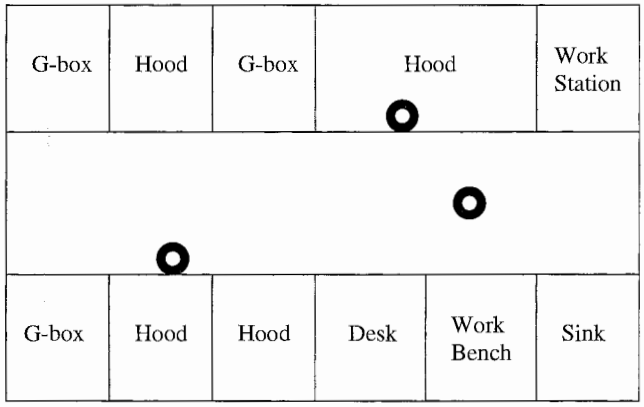

Fig. 8. Room map showing the optimized locations for CAMs (indicated by open circles).

poorly placed CAM (location 7) provided an EF of 0.28 (Table 1). This is an increase of a factor of about 3 in the level of protection for a well-placed CAM. Further, if three CAMs (locations 2, 10, and 16) were used, the EF was 0.05, a factor of about 6 in improved protection, and with no statistically significant improved protection expected beyond 3 CAMs. The improved protection for workers would be expected to be even greater in larger and heavily instrumented rooms where the aerosol mixing is poorer and the placement of CAMs would be even more critical (Whicker et al. 2002).

Studies of airflow patterns and aerosol dispersion are required for evaluation of utilization of samplers in rooms. Historically, these have been done using smoke studies. However, smoke studies provide no quantitative information on how fast aerosol is transported to CAMs nor do they provide measurement of the amount of dilution that occurs as the aerosol is transported through the rooms. Yet transport rates and dilution amount are critical in the evaluation of the timeliness and sensitivity of CAM response and ultimately the level of protection provided by the arrangement of CAMs in a room. Quantitative tracer studies, such as that described in this study, provide the necessary measurements upon which evaluations of CAM placement can be made.

This study also confirms that rooms with higher ventilation rates and more open spaces (less cluttered) provide for more rapid mixing of released aerosol through the rooms as shown by Hanzawa et al. (1987) and Whicker et al. (2002). Specifically, in the SRS laboratory studied, we found a relatively high room air exchange rate (15 room air changes per hour) and the room was relatively small (approximately 6 m × 4 m × 3 m high) with almost all of the equipment along the walls of the room. Sonic anemometer measurements of air velocities and turbulence intensity measurements made in the studied room indicate rapid mixing within the room. As reported in Whicker and Moxley (2001), the distributions of air velocities were skewed with a median of 16 cm s^{-1} and ranged from 10 cm s^{-1} to a maximum of 27 cm s^{-1}. The turbulence intensities ranged from 28% to 49% with a median of 40%. These airflow measurements combined with the small room (relatively short distances and small room volume) suggest rapid aerosol mixing rates and likely explain why transport times in the SRS laboratory (average 47 s) were significantly lower compared to larger rooms in the plutonium facility at Los Alamos National Laboratory (7–10 air changes per hour, in rooms as large as 15 m × 18 m × 5 m high), which averaged 112 s (Whicker et al. 1997). The airflow conditions that led to rapid and thorough aerosol mixing also show that if a release were to occur in this room, other workers in the room could also be exposed quickly and at the concentration nearly equal to that near the release point. Therefore, it is prudent to limit access of workers in the room to only those who are performing needed tasks, as is good health physics practice.

To fully realize maximized worker protection, we list five issues that should be further considered. **First**, in all releases studied, there has never been perfect protection (i.e., a DF = 0.0). Therefore, CAMs should be considered as one component in a multilevel protection program where reduction or elimination of accidental releases should be strongly emphasized. **Second**, however, radiological protection programs have never been successful in totally eliminating the risk of accidental releases, so additional studies toward providing more protective airflow patterns (i.e., rapidly sweep released aerosol out of the BZ and toward a nearby CAM) derived from better ventilation designs should be explored (Whicker et al. 2000c). In part, this would require better understanding of the dynamics of aerosol transport into breathing zones during accidental exposures (Drivas et al. 1996; Rodes et al. 1991; Jordan et al. 2001). This

improved understanding would also help with evaluation of the exposure fraction (EF) as a proper metric for determining optimized CAM utilization. **Third**, the stochastic nature of both exposure and aerosol sampling for radionuclides of high specific activity (e.g., ^{238}Pu) should be explored in context to CAM response and sampling rates (Scott and Fencl 1999). **Fourth**, the use of computational fluids dynamic (CFD) modeling of airflow patterns and aerosol dispersion should be explored further. CFD analysis would be useful for computer-aided design of ventilation systems and room layout for improved worker protection and is especially useful during the design or an early phase of room construction (Whicker et al. 1996; Whicker et al. 2000c; Konecni et al. 2002). Finally, a sensitivity analysis of the relative effects of varying room conditions (room layouts, ventilation parameters etc.) using CFD analysis would also provide valuable information toward evaluating CAM utilization under a variety of relevant room conditions (Whicker et al. 2000b). **Fifth**, the final optimized spatial placement of CAMs in a room selected and the resulting level protection estimated by this procedure may not be the "absolute" since not every potential CAM location in a room is tested (i.e., only 15 in the room in this study). Further, the final optimized placement may be not be guaranteed over time if there are changes in important factors which influence airflow patterns. With regards to the spatial limitations, the 15 evaluated locations were enough to predict EF of about 6% and may be sufficient protection. However, if the measured EF for a room is deemed too high, then additional testing may be warranted. With regards to temporal factors, placement should be reevaluated when significant changes in the airflow patterns might occur as a result of changes in ventilation characteristics or room layouts (Whicker et al. 2002), but this should be another active area of research.

CONCLUSION

In conclusion, this study shows that the value of quantitative airflow and aerosol dispersion studies is significant. When combined with traditional, but more limited, smoke studies, they provide valuable information for facility and safety personnel to determine the number and placement of air samplers and CAMs. In the end, worker protection from inhalation hazards will be enhanced and facility costs optimized.

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