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TITLE: POTENTIAL WORKER RISK AS A FUNCTION OF CAM AIRFLOW RATE

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Potential Worker Risk as a Function of CAM Airflow Rate

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Abstract

The goal of the continuous air monitor (CAM) system at the Los Alamos National Laboratory's Plutonium Facility (PF-4) is to have a flow rate of 1 cubic feet per minute (cfm) drawn through the CAMs. However, design limitations in the house vacuum result in many CAMs having less than 1 cfm being drawn through them. Reduced flow rates through CAMs present a compromise in worker protection. Laboratory Health and Safety personnel and DOE officials established a flow rate of 0.5 cfm or less as operationally unacceptable. This report quantitatively estimated the difference in risk to workers from a reduced flow rate of 0.5 cfm relative to the risk inherent with a flow rate of 1 cfm. I calculated risk in terms of Committed Effective Dose Equivalent (CEDE) and used units of rem. Estimates for the increase in risk for 0.5 cfm compared to 1 cfm ranged from 0.32 rem to 3.3 rem. The difference in the minimum alarm concentration between 0.5 cfm and 1 cfm was also compared and was estimated to range from 0.4 rem to 4 rem.

Introduction

The goal of the radiation protection program at TA-55 is to limit worker doses from internal exposures to zero. There are many different components of the radiological safety program that help in achieving this goal. The continuous air monitoring program is one such component. This primary purpose of the continuous air monitoring program is to reduce or eliminate inhalation exposures by providing reliable and sensitive warning of accidental airborne releases.

The adopted ALARA philosophy at TA-55 requires that the continuous air monitoring program provide optimal worker protection. This requires that the best technology, equipment, and radiological practices be used whenever it can be shown that the benefits in dose reduction outweigh the costs. There are several aspects of the current continuous monitoring program where significant improvements are needed and are under way. One such improvement is in the house vacuum system that provides air flow through the CAMS.

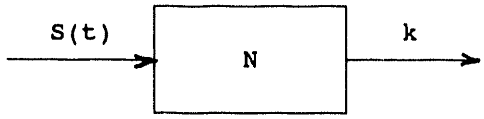
The goal of the current CAM system is to have a flow rate of 1 cfm for all CAMs. However, due to current design limitations in the house vacuum not all PF-4 CAMs have a flow rate of 1 cfm being drawn through them. TA-55 has established flow rates of less than 0.5 cubic feet per minute (cfm) as operationally unacceptable for all CAMs in PF-4. If the air flow through a CAM is less than 0.5 cfm, compensatory actions will immediately be undertaken to ensure adequate flow or room operations will be shut down. The threshold of 0.5 cfm will be revisited once the new house vacuum system is brought on-line (scheduled to be completed this summer). Clearly, reduced flow rate represents a recognized compromise in the TA-55 ALARA philosophy.

Because the new vacuum system is not scheduled to be in operation for several more months, this report explores the potential increased risk resulting from running the TA-55 CAMs at less than 1 cfm. Specifically, the report quantitatively estimates the magnitude of the added risk of running the CAMs at 0.5 cfm compared to the inherent risk in running the CAMs at 1 cfm. The risk difference is quantified in terms of worker dose resulting from airborne releases. There are two general questions that need to be answered to fully understand the effects of low flow rates: 1) what are the effects of the lower flow rates on potential worker dose from an airborne release, and 2) how does the reduction of the flow rate affect the minimum alarm concentration (MAC) in the room?

Flow Rate Effects on Potential Dose

Simplistically, the potential dose to an employee could be as much as doubled using 0.5 cfm instead of 1 cfm due to a longer time to alarm. The following calculations explore what the magnitude of this potential dose doubling could be. For this section of the report, I assume that the CAM alarms for both air flows of 1 cfm and 0.5 cfm.

One can model the concentration of airborne radioactive material in a room using the following model by assuming instant mixing and first-order rate kinetics with S(t) = release rate of radioactive material into a room as a function of time (t), N = level of radioactivity in the room, and k = the loss rate constant.



Using this model, the amount of airborne radioactive material in the room at any given time is given by the following differential equation.

$$\frac{dN}{dt} = S(t) - N*k \qquad (eqn.\ 1)$$

If the release function S(t) was known, this differential equation can be solved and by factoring in the volume of the room (V) one can determine a function describing the room concentration as a function of time or C(t).

$$C(t) = \frac{1}{V}\int_{0}^{\infty} [S(t) - N*k]\, dt \qquad (eqn.\ 2)$$

The room air concentration described in Equation 2 is complicated in that airborne release data from PF-4 show that instant mixing within the room rarely occurs. Historically over 90% of the releases in PF-4 are acute (puff) releases and the area immediate to the release shows the highest concentration. For puff releases, "radioactive clouds" are quickly created and begin dispersing and drifting, in general but not always, in a straight path toward one or more of the exhaust registers. Therefore, the worker's dose is dependent on the average concentration at their work location over the time they are in the cloud ($\bar{C}_{work}$) and the exposure time.

$$D = \frac{\bar{C}_{work}}{DAC} * T_{\min} * \frac{5000\ mrem}{2000\ DAC\text{-}hrs} \qquad (eqn\ .\ 3)$$

where: D = committed effective dose equivalent (mrem), and
$\bar{C}_{work}$ = average concentration worker is exposed to during the exposure time (dpm/$m^{3)}$,
T_{min} = minimum time worker is exposed, and
DAC = the derived air concentration for a radionuclide. I will use 4.4 dpm/m^3 (class W for Pu-239) as the DAC.

The minimum exposure time, T_{min}, will be the minimum time of either of the following: 1) the time the workers are exposed to the radioactive cloud as it passes by, or 2) the time it takes for the CAM to alarm and for workers to evacuate the room.

If T_{min} is the time it takes for the cloud to pass by, this suggests that for workers more spatially immediate to the release much of the dose received can be expected to occur very quickly as the "radioactive cloud" passes by. Here it is reasonable to suggest that much of a worker's intake may occur before the radioactive aerosols reach the CAM. For example, whether the CAM alarmed in 30 seconds or 60 seconds (1 cfm verses 0.5 cfm) adds very little in terms of dose difference if the intake occurred in the first 10 seconds. Importantly, while showing that CAM airflow effects are reduced for puff releases, this argument demonstrates the importance of CAM placement in providing early warning to unprotected workers. A study to determine optimal CAM placement is planned with the goal of greatly enhancing CAM response time.

If T_{min} is the time it takes for the CAM to alarm (assume that the workers leave immediately after the alarm) the impact of flow rates through the CAMs becomes important. The time required for the CAM to alarm is dependent on the average concentration at the CAM location, flow rate, and alarm level. The time to alarm is described by the following equation:

$$AT = \frac{AL}{\bar{C}_{cam} * FR} \quad (eqn\ .\ 4)$$

where: AT = alarm time (hr)

$\bar{C}_{cam}$ = average concentration at the CAM location from the time the cloud reaches the CAM until it alarms (dpm/m^3),

FR = flow rate in m^3/hr, and

AL = Alarm level in dpm.

It is important to note that if one assumes that the average concentrations at the CAM, $\bar{C}_{cam}$, are the same for both 1 cfm and 0.5 cfm, then AT for 1 cfm is exactly one-half AT for 0.5 cfm. However, this assumption may or may not be true. As C(t) changes over time (eqn.2), the collection rate of particles on the filter also changes and AT for 0.5 cfm could be faster or slower than one-half AT at 1 cfm. For demonstration, Figure 1 shows how the ratio of AT(0.5 cfm) over AT(1cfm) changes as a function of time following an instantaneous release with mixing and exponential loss from the room. The modelling of collection rates on filters over time would require detailed information currently not available and is beyond the scope of this report. For purposes of the report, I will assume that the average concentration does not significantly change between AT at 1 cfm and 0.5 cfm.

If AT is equal to exposure time and that the CAM alarms for both air flow rates, the relationship between the alarm time (AT) and the dose to a worker in the room can be calculated. However, several researchers (Whicker, 1993; Fairchild et al., 1991; and Brunskill and Holt, 1967) reported large dilution of Pu aerosols released in the workplace. These studies report that room dilution can be several orders of magnitude. Therefore, the calculated potential worker dose has to be modified to account for room dilution because $\bar{C}_{work}$ is usually greater than $\bar{C}_{cam}$.

$$D = \frac{\bar{C}_{work}}{DAC} * \frac{AL}{\bar{C}_{cam} * FR} * \frac{5000\ mrem}{2000\ DAC\text{-}hrs} \quad (eqn\ .\ 5)$$

I calculated the approximate dilution between the maximum area sampler and the CAM for eight releases in PF-4 during 1990 where there was a CAM alarm. I will call this the dilution factor. The median dilution factor was 8.8 and the range was 0.7 to 90. These dilution factors are consistent with those summarized by Scripsick et al. (1979). Using equations 4 and 5, I calculated and compared the differences between committed effective dose equivalents (CEDEs) for CAMs drawing 1 verses 0.5 cfm using the current alarm set point of approximately 90 dpm. The potential dose for workers, where the dilution factor was 90, would be 2.7 rem and 5.4 rem for sampling rates of 1 cfm and 0.5 cfm, respectively. This is a difference of 2.7 rem. Using the median dilution factor of 8.8, the potential doses would be 0.264 rem and 0.528 rem for 1 cfm and 0.5 cfm, respectively.

I also examined the potential dose difference knowing that workers do not exit the room simultaneously with the alarm time. One could simply add some amount of time to AT in equation 5 to more accurately model the time required to exit the room. This additional time will increase the potential doses additively and the dose differences between 1 cfm and 0.5 cfm will scale in parallel and will not change from the difference calculated in the preceding paragraph.

If one assumed instant mixing, the dose difference (equation 5 with $\bar{C}_{work} = \bar{C}_{cam}$) between these flow rates is approximately 30 mrem per individual in the room and is independent of room concentration.

Finally, I explored the effects of airflow rate on particle penetration through the sample delivery system (intake line, CAM inlet, and detector assembly) on potential worker dose. Particle penetration is the fraction of particles entering an air inlet that are collected on the filter and are available for detection by the CAM detector. The particle collection rate affects the alarm time (AT) (see equation 4) by reducing the rate at which the Pu aerosols are collected. The lower the penetration, the proportionately longer the alarm time. Strom (1972) showed that particle penetration in tubes (i.e., CAM sample intake lines) depends on flow rate and transport line design. In addition, McFarland et al. (1990) looked at the particle penetrations just through the inlet and detector filter assembly in the CAMs currently used at TA-55 and found that particle penetration dropped off rapidly for particles with sizes greater than 3 μm aerodynamic diameters (ADs). McFarland et al.(1991) developed and empirically validated a computer code (DEPO) that allows one to model the penetration of particles through a sample delivery system. This computer code was used to estimate the penetration through a sampling system that is similar to the ones used in PF-4. Figure 1 shows the delivery system used in the computer simulation. Although many, but not all, of the sample delivery lines used in PF-4 have curved large-radius bends at the top of intake tubing rather than sharp 90° bends, the code can be used to approximate the average deposition of all sample delivery lines used in PF-4 of which the designs vary considerably. Using the Figure 1 design and a lognormal particle size distribution with a geometric mean of 2 μm and a geometric standard deviation of 2, the particle penetration simulations show that particles are more efficiently transported to the CAM filters at lower flow rates (approximately 47% at 1 cfm verses 60% at 0.5 cfm). Simply stated, a flow rate of 0.5 cfm provides better penetration. The particle size distribution was selected based on several studies and is a reasonable average (Elder et al., 1974; Moss et al., 1961; and

Whicker et al., 1990). I substituted these penetration values into equation 5 to determine the potential dose differences accounting for particle penetration. The adjusted potential dose difference for a dilution factor of 8.8 would be 0.32 rem and would be 3.3 rem for a dilution factor of 90.

Flow Rate Effects on the Minimum Alarm Concentration (MAC)

Simplistically, the reduction of the flow rate (with all other CAM operating parameters held constant) could increase the MAC proportionately to the amount of the decrease in flow rate. For example, CAMs alarm at approximately 90 dpm which at 1 cfm corresponds to a MAC of approximately 15 DAC-hrs. At 0.5 cfm, 90 dpm corresponds to a MAC of approximately 30 DAC-hrs. An exposure of 30 DAC-hrs results in a potential CEDE of 75 mrem while an exposure of 15 DAC-hrs results in a CEDE of 37.5 mrem, a difference of 37.5 mrem per worker per release. Historically, it is rare that any single individual has been involved in more than one release where a positive intake is incurred resulting in more than the 38 mrem difference in a calendar year. However, the sensitivity of a CAM to detect airborne aerosols or the potential dose calculations are not as simple as the above MAC calculations suggest. The above MAC values only consider instrument related factors such as alarm set point, detector efficiency, and flow rate. Beyond instrument related factors that influence a CAMs ability to detect airborne contamination, one has to consider noninstrument factors as well (i.e., CAM placement).

Whicker (1993) reported that CAM placement may be a very important variable in determining if a CAM will detect a release. DOE (1993) also emphasized the importance of placement to provide optimal protection to the workers and found that even when a release resulted in high concentrations (i.e., > 500 DAC-hrs) as measured by the fixed air samplers the CAMs in the same room alarmed less than 35% of the time. Dilution has a major impact on the actual DAC-hrs a person could be exposed to before a CAM will alarm. In the worst case, if the dilution within the room was 90 between what the worker could be exposed to and the CAM, the worker exposure could be as high as 1350 DAC-hrs (3.4 rem CEDE) before the CAM will alarm at 1 cfm and 2700 DAC-hrs (6.8 rem CEDE) for a flow rate of 0.5 cfm. This is a potential dose difference of 3.4 rem. Using the median dilution factor of 8.8, the dose difference would be 0.33 rem. Past studies and these calculations clearly show the importance of CAM placement on the ability of the CAM to warn workers.

As in the potential worker dose section of this report, particle penetration through the sample transport line can also affect the alarm sensitivity of a CAM. Using the same penetration values of 0.47 for 1 cfm and 0.6 for 0.5 cfm, the DAC-hr sensitivities at the worker's location (using a dilution factor of 8.8) become 440 DAC-hrs (1.1 rem) and 280 DAC-hrs (0.7 rem) for air flow rates of 0.5 cfm and 1 cfm, respectively. This results in a potential dose difference of 0.4 rem. The potential dose difference in the worst case using a dilution factor of 90 would be approximately 4 rem.

Conclusions

The increase in potential CEDE as a result of having 0.5 cfm being drawn through the CAMs was calculated to be 3.3 rem for a dilution factor of 90 and 0.32 rem for a dilution factor of 8.8. This dose difference accounts for particle penetration and assumes that one or more room CAMs alarmed. I also looked at the effects of reduced air flow on the MAC. The MAC for the CAMs were 15 DAC-hrs and 30 DAC-hrs for air flow rates of 1 and 0.5 cfm, respectively. Using these MAC concentrations and accounting for room dilution, I calculated a potential worker dose. Using a median dilution factor of 8.8 and accounting for particle penetration, the calculated CEDE difference between 1 cfm and 0.5 cfm was 0.4 rem. In the worst case, where the room dilution was 90, the CEDE difference was approximately 4 rem.

These calculations show that reduced air flow affects a CAMs ability to protect workers. However, the continuous air monitoring program is just one component of the total radiation protection program. Other components include self-monitoring, radiological surveys, and fixed head air sampling. Given the state of CAM technology used in Eberline TA-55 CAMs and the current understanding of placement in rooms with highly chaotic and dynamic airflow patterns, one cannot rely solely on the CAMs as a first line defense and workers have to use other "monitoring" techniques to reliably detect releases. For example, Whicker (1993) reported that approximately 80% of releases at LANL were discovered through self-monitoring while only 5 percent of the releases resulted in CAM alarms. This suggests that the current continuous air monitoring program is not the most sensitive indicator of releases. As DOE (1993) reported on this, "It is critically important that the sites recognize the limitations of the CAM system, and that they should not rely on it beyond its present capability. The importance of using other control measures faithfully should be emphasized."

While recognizing the limitations of the current continuous air monitoring program, I believe that the current continuous air monitoring program when coupled with the remainder of the total radiological protection program (i.e., self monitoring, radiological work control, etc.) provides sufficient worker protection of inhalation exposures to allow continued NMT operations until these improvements come to fruition. This conclusion is based on historical experience and data that show that the current continuous air monitoring program, in concert with other radiological controls at TA-55, has historically contributed to limiting exposures. There have been many occasions where worker intakes were drastically reduced or prevented completely due to alarming CAMs. The effectiveness of the total radiological protection program in preventing internal exposures can be best judged based on the historical internal dose data. The TA-55 worker CEDEs from internal intakes average approximately 10 person-rem per year. This is approximately seven percent of the total effective dose equivalent for TA-55 personnel. During 1993, the cumulative CEDE was approximately 40 person-rem and was almost solely the result of a single incident where two employees received approximately 20 rem CEDE each. It is difficult to predict how much dose reduction can be achieved through better CAMs and optimal placement, but improvements can be made. While these dose levels suggest that the total radiological protection program has contributed to limiting internal intakes, it has not met the ALARA goal of zero internal dose. To meet the ALARA goal for internal exposures, LANL has implemented many improvements in the radiological protection program including work in the area of continuous air monitoring.

LANL recognized in the late 1980's that while the present continuous air monitoring program has provided a level of health protection, a significantly higher level of protection could be achieved using new technologies. This higher level of protection prompted LANL to take the lead in efforts to develop new CAMs that could be purchased at a reasonable cost. These efforts have led to a Cooperative Research and Development Agreement (CRADA) with Canberra Instruments who have since made these technologically superior CAMs commercially available. LANL has since made the Canberra CAM the lab standard. The Canberra CAM has much better sensitivity (preliminary experimental data suggest approximately 2 DAC-hrs in the field) and faster alarm times. This increase in sensitivity and alarm time is achieved through better aerosol penetration, increased air flow (2 cfm), and better radon progeny background suppression (McFarland et al., 1992). In addition, ESH-1 has studied better placement strategies that will provide for more optimal worker protection (Whicker, 1993), but more work is needed in this area. Currently, ESH-1 and other LANL groups are in the process of performing CAM placement optimization studies. These studies will combine historical release data, current operation information, and airflow studies to help determine optimal CAM placement.

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Figure 1. Ratio of alarm time (AT) at 0.5 cfm over AT at 1 cfm verses time after the release. Instantanous room mixing and exponential removal is assumed.

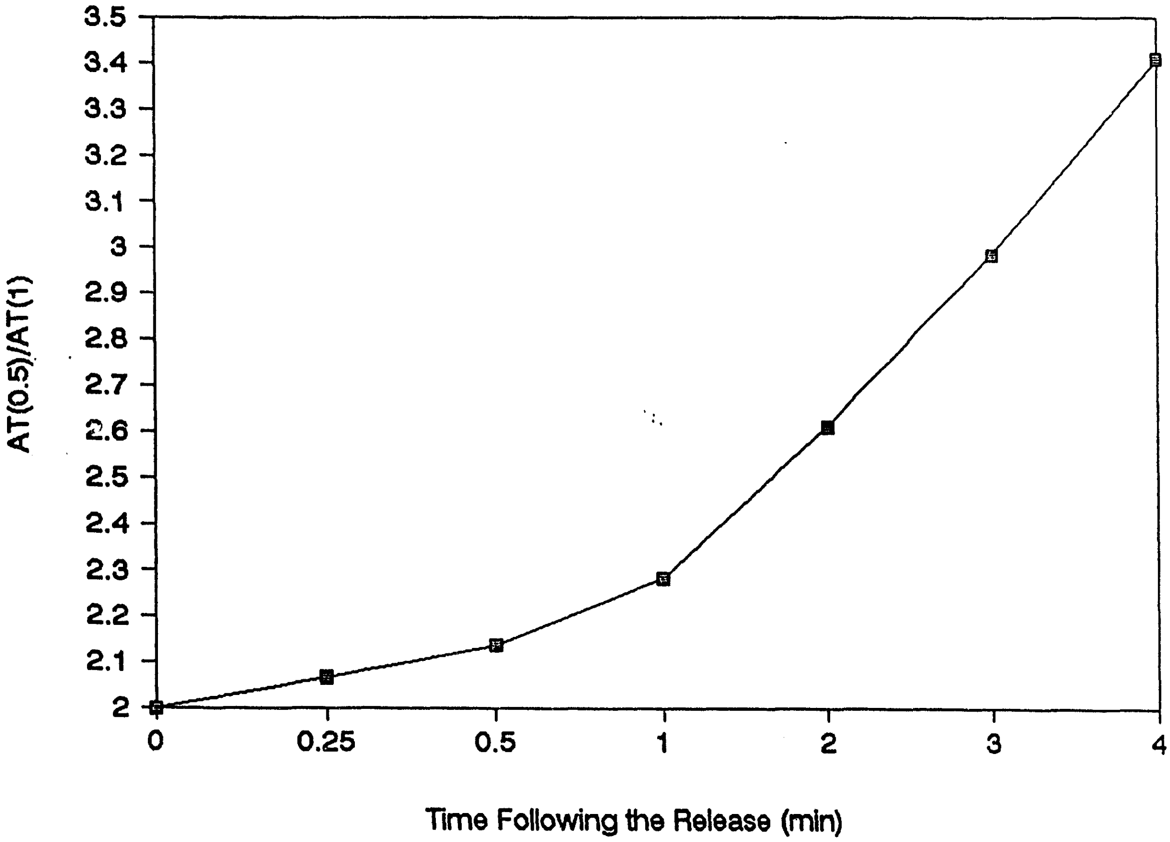

Figure 2. CAM intake tube design used to model particle penetration.