Performance Characterization of A New Cam System

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Abstract

Continuous Air Monitors (CAMs) are used in nuclear facilities to detect airborne alpha-emitting transuranic radionuclides in work areas, stacks and ducts. We have now tested the first commercial version of the original Los Alamos/Texas A&M design for its performance. The penetration of inhalable-size particles onto the CAM filter is better than 80%, with excellent uniformity of sample. With the patented diffusion screen in place, the reduction of freshly formed radon decay products is 99%.(1) With or without the diffusion screen in place, the new background compensation algorithm shows reliable detection and alarm capabilities in environments with freshly formed as well as aged radon progeny.

I. Introduction

The primary function of a Continuous Air Monitor (CAM) is to issue an alarm if the transuranic activity exceeds a preset level, so that the appropriate safety procedures may be initiated. At the same time, the alarm should not be triggered unnecessarily by the presence of the naturally occurring radon progeny. The Department of Energy (DOE) Order 5480.11(2) includes a requirement that a CAM should be able to alarm at an exposure level of 8 DAC-hours under controlled laboratory conditions. However, designing a CAM that can reliably alarm at 8 DAC-hours under field conditions has been a difficult goal to achieve.

Some CAM inlet designs have been shown to have difficulties obtaining a representative sample of the inhalable-size particles (10 �m aerodynamic equivalent diameter) without significant loss or bias.(3) Some designs show significant non-uniformity of filter deposits.(3,4) If the aerosol particles are predominantly deposited near the edge of the filter, the transuranic concentration in the air will be underestimated; and if the deposits are mainly in the center of the filter, the concentration will be overestimated.(5) Also, the commonly used numerical algorithms for subtracting the counts in low energy tail of the 6 MeV radon daughter sometimes have difficulty distinguishing the transuranic counts from the radon daughter interference, if the radon level is elevated.

To address these difficulties, the Los Alamos National Laboratory, together with the Aerosol Technology Laboratory of Texas A&M University launched an effort to develop a new generation CAM. This effort had several important goals including: obtaining a representative air sample and depositing it uniformly on the filter of the unit; partial removal of the radon daughter products from the air stream; and, an accurate background compensation algorithm. In addition, it had to reliably alarm at an exposure level of 8 DAC-hours or less with a minimum false alarm rate.

Several of the design goals were already reached during the development of the first prototype. The problems of obtaining representative air samples, removing a large fraction of the radon daughter products from the air flow and producing uniform sample deposits were resolved during that phase of the project. A description of the results obtained with the Los Alamos/Texas A&M CAM prototype have been reported elsewhere.(1,3,5,6) In this work, we report on the testing of the first commercial version developed from the original Los Alamos/Texas A&M design. In addition to repeating the tests on the penetration of inhalable-size particles onto the CAM filter and the uniformity of the sample, we have included tests to verify the alarm capabilities of the new background compensation algorithm which has been added to this commercial version.

II. Background Compensation Algorithm

To illustrate why a sophisticated background compensation algorithm is required, let us consider a typical CAM spectrum as illustrated in Figure 1. It has four distinctly separate regions which are marked as regions 0 to 4. Region 0 below channel X_0 is of no particular interest. Region 1 between channels X_0 and X_1 denotes the interval which contains all the transuranic counts. Region 2 between channels X_1 and X_2 denotes the channels for the 6.0 MeV background radiation. Region 3 between channels X_2 and X_3 denotes a region for the 7.68 MeV background peak, and Region 4 is the spectrum above X_3. However, as can be seen from Figure 1, the background peaks have pronounced tails, which extend well into Region 1 and must therefore be subtracted from it to calculate the net transuranic content in the spectrum.

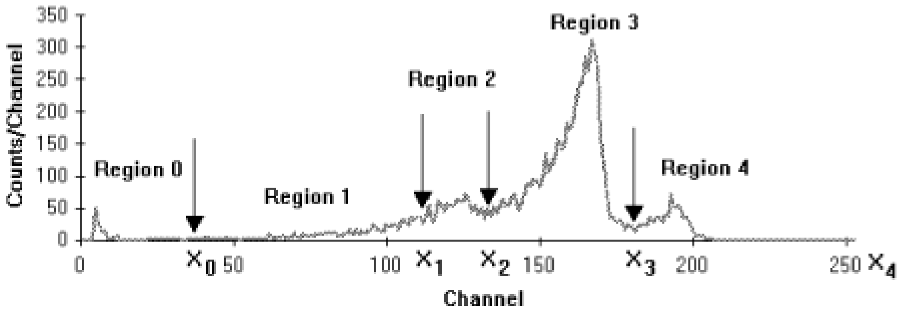

Figure 1 Typical CAM spectrum.

To calculate these tails, we have adapted a method from a more general purpose alpha spectroscopy algorithm.[7] We first calculate the "valley" channels, X_n, based on an energy calibration and the known peak energy of the transuranic nuclide of interest as well as the known peak energies of the radon progeny. In addition, we assume that the spectrum is a linear combination of single energy response functions. This means that at each "valley" channel, X_n, its contents are a linear combination of the counts from the tails of the peaks to the right of it, i.e. the counts at X_3 are caused by the 8.78 MeV peak, at X_2 by the 8.78 MeV and the 7.68 MeV peaks, etc. Furthermore, we assume that the tail of each peak below the "valley" point to the left of it can be described by a single exponential function of the form

$$Y_i \quad e^{m\ X_i \quad b}$$

(Equation 1)

where Y_i are counts in channel X_i, and m and b are constants.

According to this model, the 8.78 MeV tail will pass through values that represent only its contribution at X_3 and X_0. For a more representative value, particularly since the low counts of the CAM spectra mean poor statistics, we define the contribution at channel X_3 as an average of 2k+1 channels about it, that is

$$Y_{3(av)} \quad \frac{1}{2k\ 1}{}_{i\ X_3\ k}^{X_3\ k} Y_i$$

(Equation 2)

where we choose k = 2.

At channel X_0, we define the contribution due to the 8.78 MeV peak, $Y_{0(8.78)}$, as

$$Y_{0(8.78)} \quad \frac{{}_{i\ X_3}^{X_4} Y_i}{{}_{i\ X_0}^{X_4} Y_i} \quad Y_{0(av)}$$

(Equation 3)

where $Y_{0(av)}$ is calculated around X_0 using Equation (2). In principle, the numerator in Equation (3) should include the counts in the tail portion of the response function as well. However, due to the fact that the contribution of the tail to the total sum is rather small, we assume Equation (3) to be a good approximation.

The tail function of the 8.78 MeV peak can now be determined by substituting X_3, $Y_{3(av)}$, X_0, and $Y_{0(8.78)}$ into Equation (1) and solving for the coefficients $m_{8.78}$ and $b_{8.78}$. After subtracting the response function of 8.78 MeV peak from the spectrum channel by channel, the process is then repeated for the 7.68 and 6.05 MeV peaks. The transuranic net area is the remainder after all three background peaks have been subtracted, namely:

$$A_{Pu} \quad \overset{X_1\ 1}{\underset{i\ X_0}{}} \left(Y_i \quad e^{m_{8.78} X_i \ b_{8.78}} \quad e^{m_{7.68} X_i \ b_{7.68}} \quad e^{m_{6.05} X_i \ b_{6.05}} \right)$$

(Equation 4)

Theoretically, the counts in the tails are Poisson distributed; however, the tail integral is not. To be conservative, we use the net area of all four peaks to estimate the net area uncertainty for the transuranic counts. We then require that its area must exceed the area uncertainty estimate multiplied by a desired confidence factor for the transuranic nuclide to be detectable.

All of the background compensation calculations are performed by a separate control unit at the end of a preset count cycle for each sampling head connected to it. Whether an alarm will be indicated is dependent on whether the detected transuranic count rate translates to an exposure (in DAC-hrs) that is higher than the currently selected "slow" alarm limit. In addition, each sampling head calculates a "fast" alarm every 30 seconds based on the counts collected within the last 30 seconds. The "fast" alarm is indicated if the number of counts in region 1 exceeds a preset level, and the ratio of average counts per channel in region 1 to the average counts per channel in the window from X_1 to the 6.0 MeV peak exceeds a factor of two.

III. Experimental Procedures

The tests to verify the performance of the new CAM sampler were primarily conducted at the Texas A&M wind tunnel facility. The experimental protocol on how to verify the penetration of aerosol particles as a function of the aerodynamic equivalent size has been previously described in detail.[6] It basically involves generating a uniform non-radioactive, but measurable (fluorescent tracer) aerosol concentration profile in the test section of the wind tunnel through the use of a vibrating jet atomizer.[8] The aerosol is then simultaneously sampled with the CAM sampling head and an isokinetic probe fitted with a filter collector. At the conclusion of the test filters from the CAM and the probe are removed and the aerosol penetration is determined from the ratio of the masses of the fluorescent tracer collected by the CAM and the isokinetic probe, and the flow rates through the two samplers. The size of the aerosol produced by the atomizer is verified with a microscope both at the beginning and at the end of each test. At least three replicate tests were run at each aerosol size to obtain a measure of the reproducibility of the experiment and to provide an uncertainty estimate for the result.

The tests to verify uniformity of deposition consisted of operating the CAM sampler in the wind tunnel for a slightly longer time than necessary for the penetration studies (15 to 45 minutes) to collect a sufficient mass of the tracer such that it would be quantifiable even with small subsamples. The filter was then cut into 20 subsamples and quantified for uniformity of deposition. This experiment also included at least three replicate measurements at each test condition to obtain an estimate of the reproducibility of the experiment.

To establish how well the diffusion screen removes radon daughters, we pumped filtered, clean air through 200 liters of high-grade uranium ore to spike it with radon. The air was then pumped through a baffled chamber to mix it thoroughly and to allow the radon progeny to form. At the other end of the chamber, the air was pulled through a CAM unit and an open-faced filter. The CAM unit and the open-faced filter were operated for several 5 minute periods, first at 28.3 L/min and then at 56.6 L/min air flow. Within 1 minute of the termination of each exposure, both filters were counted to establish their activities using the three-count technique of Nazaroff[9]. The amount of removal of the unattached fraction can be calculated from the ratio of the ^{218}Po activities in the two filters. These results have been previously reported.[1]

In the present studies, we used the chamber with the radon progeny generator to test the ability of the background compensation algorithm to issue reliable "slow" alarms. For this purpose, we generated two different types of radon environments. To simulate clean laboratory environments, the air in the mixing chamber air was kept clean to keep the radon daughters in a mostly unattached form. To simulate less clean environments, we injected aerosols into the mixing chamber to act as condensation centers to make the radon progeny appear to the CAM in a mostly attached form. The unattached radon daughter environment was tested with and without the diffusion screen in place. A summary of the three different types of environments (A, B, and C) is shown in Table 1.

Table 1. Radon environments used to test the slow release alarm.

Environment Type	Radon Progeny in Ambient Air (pCi/L) RaA	RaB	RaC	Percent of Radon Progeny Attached RaA	RaB	RaC
A (Unattached RD, Screened Inlet)	1.025 ±0.095	0.065 ±0.039	-0.032 ±0.029	2.4 ±2.3	0.6 ±14.9	-46.2 ±48.4
B (Unattached RD, Unscreened Inlet)	0.591 ±0.074	0.023 ±0.030	-0.002 ±0.022	3.1 ±2.9	3.7 ±6.0	-191.1 ±2370
C (Attached RD, Unscreened Inlet)	1.706 ±0.139	0.331 ±0.060	0.101 ±0.048	90.6 ±10.9	107.9 ±28.3	137.3 ±81.2

The amount of radon daughters in the air stream was established from the activity measured from the open-faced filters. The values indicated in the table represent the radon concentration outside the CAM unit. Since we had previously established[1] that the diffusion screen removes 99% of the freshly formed (unattached) radon daughter products from the air stream, the percentage of attachment also shown in Table 1 can easily be calculated from the ratio of the activity in the open-faced filter and the activity in the filter inside a CAM unit with the diffusion screen in place.

The CAM unit was operated at a flow rate of 56.6 L/min for a 5 minute count cycle in these three environments with a clean filter as well as with a filter that had previously been loaded with a small amount of plutonium. Two different plutonium loaded filters, one with approximately 15 cpm and the other with about 35 cpm of plutonium were used for these tests. Neither one exceeds the 8 DAC-hr limit under such conditions. We therefore set the alarm threshold low enough, such that if plutonium was detected, the unit would issue an alarm. At each count cycle, the resulting spectrum was analyzed for both the "slow" and the "fast" alarm. For this particular test, the sampling head did not have the capability to calculate the "fast" alarm, so the fast alarm was calculated at the end of the count cycle for comparison only. In actual usage of the CAM system, the "fast" alarm will be calculated in the sampling head and can result in a truncation of the count cycle. In a separate test at Los Alamos, we created an environment with a pre-loaded filter where the exposure exceeded 8 DAC-hrs.

IV. Results and Discussion

The results of the aerosol penetration study for the Canberra prototype are shown in Table 2. For comparison, the results for the original Los Alamos/Texas A&M model are shown for one of the cases. The results for the 56.6 L/min flow rate case are also shown graphically in Figure 2. In the figure, the curves represent polynomial fits through the data points. It is clear that the Canberra prototype exhibits the same characteristics as the original design.

Table 2. Aerosol penetration characteristics of the original prototype and the Canberra prototype.

Wind Speed (m/s)	Air Flow (L/min)	CAM Prototype	Aerodynamic Particle Size (µm)	Penetration Percent	Standard Deviation Percent
1.0	56.6	Los Alamos	5	101.9	3.2
			10	79.8	0.6
			15	54.4	1.4
1.0	56.6	Canberra	5	98.6	1.7
			10	81.2	2.0
			15	63.3	1.3
0.5	56.6	Canberra	3	95.1	2.5
			5	94.2	0.9
			10	86.6	1.6
			15	61.3	0.8
			20	38.8	0.8
0.5	28.3	Canberra	3	95.0	3.7
			5	88.9	1.9
			10	75.3	1.3
			15	42.1	0.4
			20	18.3	0.6

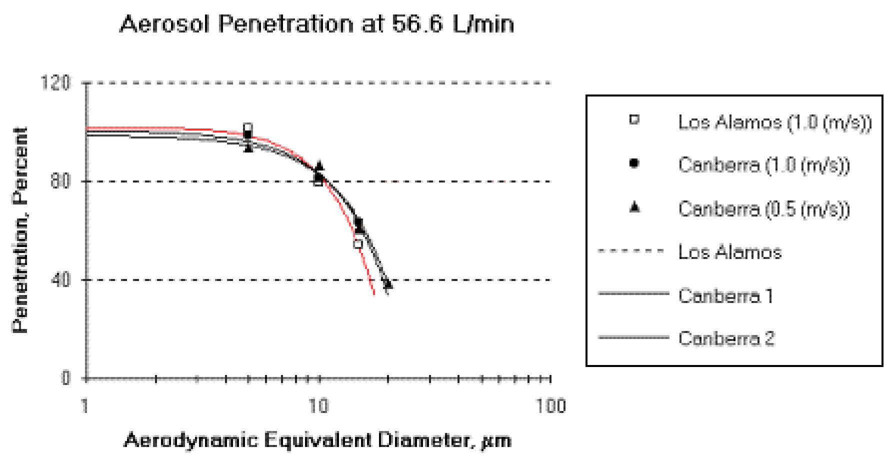

Figure 2. Comparison of the aerosol penetration results from the Los Alamos / Texas A&M prototype and the Canberra prototype.

The results of the uniformity of deposition studies for the Canberra prototype are summarized in Table 3. Here, the coefficient of variation represents the standard deviation of the aerosol mass per unit area in the subsamples to the mean mass/area on the complete filters. The values are normalized to a mean of unity and established with a wind speed of 0.5 m/s for 10�m particle size. For comparison, we have also included the results for the Los Alamos/Texas A&M prototype. While the measurements were not under identical conditions, it can clearly be seen that the results for the Canberra prototype are at least as good as those of the original design.

Table 3. Uniformity of aerosol deposits.

CAM Prototype	Wind Speed (m/s)	Inlet Configuration	Flow rate (L/min)	Coefficient of variation (%)
Canberra	0.5	Radial	56.6	7.9
		In-line	56.6	8.8
			28.3	5.4
Los Alamos	0.3	Radial	56.6	14.6
			28.3	14.1
		In-line	56.6	13.7

The results of the background compensation tests are shown in Table 4. As can be seen from the table, no false alarms were observed for the clean filters in any of the environments for the "slow" alarm algorithms. For the pre-loaded plutonium filters, it indicates the presence of the transuranic counts quite reliably in all environments. Comparing the results for environments A and B, it is also evident that the presence of the diffusion screen enhances the capability of the algorithm.

The "fast" alarm calculations are based on a simplified algorithm and are normally done in the sampling head. For this particular test, the sampling head was not equipped with the "fast" alarm capability and the results shown in Table 4 are shown for full count cycles for illustration only. However, it is noteworthy that there are no false alarms for the clean filters. Furthermore, the presence of the diffusion screen helps the "fast" alarm algorithm as well, as evidenced by the results from environment A.

Table 4. Fast and slow alarm results.

No. of Measurements	Environment Type*	Filter Type	Alarm (True/False) Fast	Slow
177	A	Clean	0/177	0/177
94	A	Pre-loaded	7/84	93/1
87	B	Clean	0/87	0/87
76	B	Pre-loaded	0/76	71/5
46	C	Clean	0/46	0/46
12	C	Pre-loaded	0/12	12/0

* See Table 1.

The results for the separate exposure test at Los Alamos are shown in Figure 3. The first 15 measurements were done with no air flow to establish the count rate for the pre-loaded plutonium. For the rest of the measurements, the count cycle time was set to 15 minutes and the air flow to about 47.5 L/min. It can be noted that the output from the CAM is a set of very consistent readings for both the counts/min and the DAC-HRS.

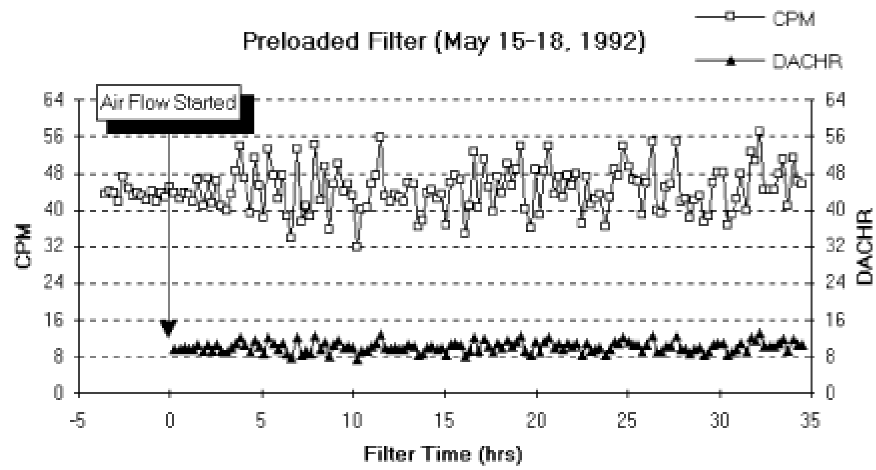

Figure 3.
Observed net plutonium count rate and the calculated DAC-hr exposure for a pre-loaded plutonium filter.

V. Conclusion

As can be seen from the results presented in this study, the Canberra CAM unit clearly meets the design criteria of the original Los Alamos/Texas A&M CAM design. Furthermore, in tests conducted in a variety of environments, the new background compensation algorithm has proven to give reliable and accurate results at or near the 8 DAC-hr exposure limit.

VI. References

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