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Continuous Air Monitor Operating Experience Review

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CONTINUOUS AIR MONITOR OPERATING EXPERIENCE REVIEW

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Continuous air monitors (CAMs) are used to sense radioactive particulates in room air of nuclear facilities. CAMs alert personnel of potential inhalation exposures to radionuclides and can also actuate room ventilation isolation for public and environmental protection. This paper presents the results of a CAM operating experience review of the DOE Occurrence Reporting and Processing System (ORPS) database from the past 18 years. Regulations regarding these monitors are briefly reviewed. CAM location selection and operation are briefly discussed. Operating experiences reported by the U.S. Department of Energy and in other literature sources were reviewed to determine the strengths and weaknesses of these monitors. Power losses, human errors, and mechanical issues cause the majority of failures. The average "all modes" failure rate is 2.65E−05/hr. Repair time estimates vary from an average repair time of 9 hours (with spare parts on hand) to 252 hours (without spare parts on hand). These data should support the use of CAMs in any nuclear facility, including the National Ignition Facility and the international ITER experiment.

I. INTRODUCTION

A continuous air monitor (CAM), also called a constant air monitor, is the basic device used to sample room air in nuclear facilities and protect workers from airborne radioactivity hazards. An early generation CAM is shown in Figure 1. The allowable radionuclide concentration limits for personnel inhalation exposure in the U.S. are given in 10CFR20 and 10CFR835[1,2] but the means by which an employer will determine these exposures is not specified in the regulations. The long-standing, typical method for measuring the concentration of radioisotopes in air, and thus evaluating the possibility of inhalation exposure from air contamination, is to pass a measured quantity of air through a collection medium and then read the activity of whatever airborne material collects on the medium. Filter paper is typically used as the collection medium. The air flow is usually forced through the filter paper, such as by a blower or small vacuum pump. Either device moves air at a measured rate, usually about 0.5–1 L/sec (1–2 ft^3/min), across the filter paper. A radiation detector mounted close to the filter paper is used to measure the activity of any collected material.[3] Radiation detectors are typically Geiger-Muller counters or scintillation counters with photomultiplier tubes.

Fig. 1. A typical first generation continuous air monitor.

CAMs are used to monitor for airborne contamination in nearly every nuclear and nuclear-related installation, including reactors, hot cells, fuel processing and storage buildings, waste processing and storage facilities, particle accelerators, test reactors, and fusion energy experiments. CAMs have been used for over 60 years. One of the earliest designs of a CAM was put in service at Oak Ridge National Laboratory. In 1944, units were set up within and outside of Oak Ridge buildings to detect iodine from radioactive lanthanum processing operations.[4] Because of the widespread and long-term use of CAMs, operating experience data were readily available for this review.

It is noted that one of the most important issues regarding CAM effectiveness is location selection so the CAM unit will draw air samples that are representative of the worker breathing air.[5,6] It is not uncommon to use two or more CAMs in a given room or building area; overlapping coverage ensures that if one CAM fails, the room or area is still being monitored. Overlapping coverage also allows multiple location samples to calculate reasonable average estimates of radionuclide concentrations in room air. Consequently, a large facility can use several dozen CAMs throughout its radiation areas. As a generality of CAM operation, a large facility will also have a small set of spare units on site; a rough rule of thumb would be up to 10% of the number of deployed CAMs to serve as replacements for failed monitors. This paper reviews monitor operating experiences and good practices and gives some reliability and maintainability values for these instruments.

II. EXPERIENCE DATA ASSESSMENT

The U.S. Department of Energy (DOE) operates an Occurrence Reporting and Processing System (ORPS) database to record equipment faults and human errors at DOE facilities.[7] The reporting period of 1990 to the present has encompassed thousands of CAM units across the DOE Complex. A search of the database narrative descriptions for “continuous air monitor” returned 415 ORPS reports (see Table I). Some reports were deleted from this study because they described a CAM correctly responding to airborne contamination; the majority of these reports occurred during decommissioning and dismantlement activities. Other reports were deleted because they referred to stack monitors rather than room air monitors. A third subset of the reports was deleted because a CAM was mentioned but the report described some other, unrelated equipment failures. These deletions left 219 reports attributable to personnel safety CAMs. As derived from Table I, 29.7% of failures were electrical (including loss of power and power supply problems), 26.9% of the failures were mechanical (mainly in the air pumping portion of the units), human errors gave 27.4% (roughly three errors by authorized CAM workers to each non-CAM worker error), 8.2% were radiation detector tube faults, and 7.8% of the reports were electronics faults.

In the early 1990s, Lingren and Hitzman polled nuclear power plants about radiation monitoring system performance with a questionnaire.[8] Failures of Geiger-Muller and photo-multiplier tubes were noted to be one of the widespread issues at the 55 plants that responded to the questionaire. This is much different than the 8.2% of detector failures shown in Table I. Reasons for this discrepancy are not clear. Operating environments would appear to be similar and should not be a factor in this difference. Perhaps manufacturing improvements occurred in the late 1990s and early 2000s.

One interesting issue is the number of CAM failures where the CAM did not annunciate a fault or otherwise issue some type of trouble alarm. In human-error-caused failures, the CAM did not annunciate 88% of the time. In 42% of the mechanical faults and 38% of the electrical faults, the affected CAMs did not issue a trouble alarm. The only way personnel learned of the failure was either from daily testing or from an alert staff member passing by and noting that the CAM was not operating. Therefore, the periodic (daily or perhaps weekly) inspections that room air monitor CAMs receive is warranted and is a best practice for this type of instrument, at least for the presently used level of technology.

Periodic checks are warranted for other types of monitors as well. Experience data with nuclear criticality alarms showed that for a 1-year test interval, the failure of the monitoring system to alarm on demand was 1.7E−03/demand; for a 1-month test interval, the failure rate was 1.3E−04/demand.[9] This is a full order of magnitude lower failure rate gained by the more frequent testing because the higher frequency of testing identifies both system faults and incipient faults or weaknesses before such faults propagate into device failure. Frequent testing that does not create additional system wear or decrease useful system life is a benefit to operational reliability and is a best practice.

III. RELIABILITY AND MAINTAINABILITY DATA

The ORPS reports describe the failure modes of CAM units but do not give enough information on units in use and time periods to calculate failure rates. Instead, the literature was searched for published failure rate data on air monitors. Several values were found and are given in Table II.[10–13] Also, various Idaho National Laboratory (INL) records have been reviewed and provide enough data to support an order-of-magnitude failure rate calculation. A typical count of four faults per year at an INL facility gives a point estimate of 4/[(44 units)(8760 hr)] or 1.0E−05/unit-hr. The 1.0E−05/unit-hr failure rate range is a reasonable first approximation for the INL units in use. Taking the “all modes” failure rates in Table II and performing a geometric mean value for those data values gives 2.6E−05/unit-hr, which yields good agreement with the INL cursory value and sets a suggested “all modes” failure rate value for CAMs of 2.6E−05/unit-hr based on the literature data. The INL data also gave 16 false radiation alarm events over 13 years, so 16/[(44 units)(13 yr)] = 0.03 false alarms per CAM-year. There were no INL events of failure to alarm when required by airborne activity. There have been too few events of airborne activity challenging the INL CAMs, so any statistical estimate of failure to alarm on demand is not meaningful. If more demands to operate had occurred, the “alarm on demand” failure rate could be calculated for INL CAMs.

TABLE I. Continuous air monitor data from DOE events reported in ORPS.

Fault Category	Subcomponent or Error	Fault Count	CAM Alarmed the Fault[a]	CAM Did Not Alarm Fault
Mechanical Faults				
Air flow problem	Seal, solenoid, tube, air hose, valve, rotometer	11	6	5
Air flow environmental problem	Windstorm, dust accumulation	7	0	7
Alarm	Alarm not functional	3	1	2
Cabinet	Various cabinet problems	3	2	1
Cabinet	Wheels	1	1	0
Cabinet	Light bulb	2	1	1
Maintenance alarm	Unknown fault caused alarm	7	7	0
Motor	Blower motor failure/vacuum pump failure	12	10	2
Motor	Blower motor switch	2	1	1
Motor	Bearings	1	1	0
Motor	Belt	3	0	3
Recorder	Strip chart	3	1	2
Timer	Timer	1	0	1
Early life faults in new components	Unknown	3	3	0
Subtotals		59	34	25
Electrical Faults				
Annunciator	Panel problem, interface board	4	1	3
CAM alarm test or spurious alarm	Unknown fault caused alarm failure or spurious alarm	3	1	2
CAM reading	Erratic readings to control room, unidentified electrical component	6	4	2
Loss of line power	Damaged wiring from rainwater, wiring pulling loose, poor connection, short circuit, fuse, sensitive power connection	10	7	3
Loss of line power	Reason not listed in ORPS	18	11	7
Loss of power supply	Diode shorted out	7	5	2
Power supply problem	Power flux, defective supply	6	1	5
Power supply problem	High voltage error	1	1	0
Power supply problem	Noise interference	8	8	0
Power supply problem	Pre-amplifier failed	2	1	1
Subtotals		65	40	25
Electronic Faults				
Display	Unreadable LED	2	2	0
Software	Math error	2	2	0
Software	Random access memory check sum error	12	11	1
Software	Circulatory software error message	1	1	0
Subtotals		17	16	1
Radiological Faults				
Detector failure	Unidentified Geiger-Müller tube, photomultiplier tube fault	16	11	5
Detector	Mylar torn	1	1	0
Detector	Rate meter stuck	1	1	0
Subtotals		18	13	5

TABLE I. (continued).

Fault Category	Error	Fault Count	CAM Alarmed the Fault[a]	CAM Did Not Alarm Fault
Human Error—CAM Worker[b]				
Human error	Air intake not repaired, vacuum line left off, vacuum left unplugged	2	0	2
Human error	Air flow set too high	1	1	0
Human error	Air flow set too low	1	0	1
Human error	Air flow blocked, glove on box, hand on air intake	2	1	1
Box problems	Door not closed properly on CAM cabinet	1	1	0
Box problems	CAM covers not replaced correctly	1	0	1
Calibration	Overdue calibration	7	0	7
Calibration	Wrong set-point for radiation level	5	1	4
Calibration	Used wrong check source	1	0	1
Human error	Forgot to plug in, forgot to put valve line back in, forgot to reopen valve, forgot to put filter paper in	9	0	9
Human error	Forgot to remove from test mode	2	0	2
Outside cause	Borrowed contaminated CAM to use	1	0	1
Outside cause	Fail to turn building thermostat to correct temperature	1	0	1
Training error	Incorrect inspection procedure followed	4	0	4
Training error	CAM location placement error	2	1	1
Training error	Maintenance error- dirty clogged pump	1	0	1
Training error	Untrained in reading rated values	2	0	2
Training error	Wrong part used	1	0	1
Subtotals		44	5	39
Human Error—Non-CAM Worker[b]				
Human error	Air flow blocked, covered air intake	1	0	1
Human error	Informed supervisor did not change out CAM before calibration expired	1	0	1
Human error	Shift manager did not reconnect vacuum pump	1	0	1
Outside cause	Electrical work not pertaining to CAM dislodged leads	1	1	0
Outside cause	Saw cut power	1	1	0
Training error	CAM location error	1	0	1
Training error	Operator did not see/understand CAM alarm	1	0	1
Training error	CAM turned off, unplugged	8	0	8
Training error	Unplugged vacuum pump to quiet the area	1	0	1
Subtotals		16	2	14

a. Alarm designation includes maintenance, trouble, alert, or evacuation types of alarms that annunciated the fault.
b. CAM workers are those trained and authorized to work on CAMs.

Regarding maintainability, a crucial piece of data is the repair time for the units. Table III gives some data gleaned from the ORPS reports on maintenance times, combined with some averaged maintenance data from INL facilities. The CAM testing times are probably most applicable across various nuclear sites.

The maintenance times have many variables, including the number of electronics or instrumentation technicians on staff that are qualified to repair a CAM, the number of spare CAM units held on site, the number of spare parts kept on hand or in stock rooms versus ordering, and delivery time to the site. Some of the INL CAMs are very old designs (some more than 40 years old) and were manufactured by companies that have since gone out of business. The older units have created problems with component failures, requiring more and more technician time for repairs as the units reach the end of their useful lifetime. Obtaining appropriate spare parts has become problematic for these older units. Lingren and Hitzman noted the same issue of CAM obsolescence at power plants.[8] Small numbers of newer, digital CAMs have been purchased annually at the INL to replace the most aged units, targeting the most crucial locations first.

TABLE II. Radiation monitor failure rates from generic data sources.

Component Description	Failure Mode	Failure Rate (/hr)	Upper Bound Failure Rate (/hr)	Reference
Radiation instrument	All modes	1.43E−05	1.99E−05	[10]
	Zero or maximum output	1.943E−06	2.693E−06	[10]
	No output	0.972E−06	1.347E−06	[10]
	No change of output with change of input	2.320E−06	3.216E−06	[10]
	Erratic output	3.161E−06	4.382E−06	[10]
	High output	1.595E−06	2.211E−06	[10]
	Low output	1.595E−06	2.211E−06	[10]
	Incipient failure	2.755E−06	3.819E−06	[10]
Radiation instrument	All modes	1.098E−05	3.310E−05	[11]
	Zero or maximum output	2.28E−06	6.86E−06	[11]
	No output	No value given		[11]
	No change of output with change of input	1.79E−06	5.39E−06	[11]
	Erratic output	2.42E−06	7.28E−06	[11]
	High output	1.21E−06	3.64E−06	[11]
	Low output	1.20E−06	3.64E−06	[11]
	Incipient failure	2.08E−06	6.29E−06	[11]
Radiation monitor	Drift	3.82E−05	1.98E−04	[12]
	Failure	3.80E−05	8.32E−05	[12]
CAM	All modes	1.1E−04	Not given	[13]

TABLE III. Maintenance and repair times for CAMs.[a]

Activity	Average Time	Source
Technician performs daily check of CAM operability	≈ 5 minutes	INL data
Technician investigates a suspected false CAM alarm; checks CAM filter paper with portable meter	12 minutes	INL data
Technician restores power to an inadvertently de-powered CAM, verifies operation	5 minutes	INL data
Technician performs CAM weekly filter change	30 minutes	INL data
Technician performs monthly CAM interlock check	30 minutes	INL data
Replace a failed CAM with a spare unit	30 minutes	INL data
	1.9 hours	[7][b]
CAM unit repair in instrument shop with spare parts on hand	9 hours	INL data
	15.2 hours	[7][b]
CAM unit repair in instrument shop, requires ordering parts from vendor	10.5 days	INL data
	8 days	[7][b]
CAM mean time to repair	43.5 hours	[13]

a. These times have been averaged from a combined set of older CAMs and newer digital CAMs. The times are considered to be generic for CAM units. Technician activities do not include travel time to the CAM unit.
b. A few of the ORPS reports gave repair times and these times were averaged for presentation in this paper.

As an example of the differences between sites, consider the data reported from the DOE Hanford site.[13] Grigsby et al. give a mean time to repair (MTTR) value for CAMs of 43.5 hours. That value was found from a sample of four stack CAMs operating over a 2-year period; no MTTR data for room air CAMs were found in the literature. At the INL, the average CAM repair time with spare parts on hand was 9 hours; without spare parts on hand, the average was 252 hours, meaning parts procurement time drives up the CAM downtime. Averaging these two INL MTTR values gives 130.5 hours, a factor of three variance from Grigsby's value. Maintainability data can have such variability for the reasons described above.

As an example of the use of these data, consider a facility using 50 CAM units. With the average failure rate of 2.65E−05/unit-hour times 50 units, inverting the result gives ≈ 755 hours for mean time between CAM failures. Therefore, the set of CAMs would experience one failure roughly once per month. Using the data from Table III shows that the MTTR is much shorter than 755 hours, so perhaps one or two spare units on hand to replace failed units is adequate (i.e., 2–4% spares). If the CAMs are positioned to give good overlapping coverage of facility areas then no spares would be needed as replacements during calibration sessions. Otherwise, another one or two spare units might be needed for use as replacements during calibration sessions. Summing the daily, weekly, and monthly checks in Table III gives an average of 62 hr of technician time per CAM per year.

IV. CONCLUSIONS

The CAM experiences show that the highest percentage of failures is in power losses and in electrical components, followed by human errors and failures in the mechanical portion of these monitors. The current approach in the DOE Complex is to quickly replace a faulted unit with a spare CAM and take the out-of-service unit to an on-site shop for repairs. Daily operability checks and weekly functional tests are warranted because continuously operating CAMs, with their problems in drawing air and keeping power supplied to the unit, need frequent checks to verify proper operation. These faults are not always annunciated as trouble alarms by the CAM unit, so daily visits keep the units available to perform their tasks. Daily visits are a best practice for CAM operability.

On a positive note, the detector tubes appear to operate well. The reports only showed 8.2% detector head failures over the 18-yr time span of occurrence reports.

The literature search for CAM failure rates yielded the values given in Table II. Averaging the "all modes" failure rates produced a mean of 2.65E−05/unit-hr, which was in general agreement with experiences from the INL. This value is therefore reasonable to apply to CAM units if no component-specific, site-specific, or otherwise better data sets are available.

The failure rates and repair times are useful for personnel safety assessment and for facility radiological control planning. Given the estimated number of CAM units intended for a facility like ITER, planners can estimate an initial number of spare CAM units to have on hand. The time data for CAMs can be used to estimate the number of radiological control technicians needed to support the CAM checks and calibrations. Repair times can be used to help estimate the number of spare units needed and the size of the technician staff needed at the facility.

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