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Radiation Protection Instrument Reliability and Maintainability Data

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ABSTRACT

This report is a collection of reliability and maintenance data on several types of radiation protection instrumentation. Some radiation detectors are used for personnel safety; others are used for environmental stewardship. Six types of instruments are addressed in this report. These are: continuous air monitors, tritium room air monitors, facility vent stack monitors, tritium bubbler monitors, tritium in effluent water monitors, and general purpose radiation survey meters. Literature searches, operating experience data, and occurrence reports were used to identify failure modes and to estimate quantitative failure rates for several general types of radiation protection instruments. Likewise, data on instrument repair has been found when possible and used to estimate the mean time to repair. These data can be useful for facility safety assessment, personnel safety assessment, environment assessment, and for equipment and labor planning purposes.

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FIGURES

ACRONYMS

CAM	continuous air monitor
CFR	Code of Federal Regulations
DAC	derived air concentration
DOE	Department of Energy
GBq	giga-becquerels
h	hour
HT	hydrogen tritium molecule
HTO	hydrogen-tritium-oxygen molecule
INL	Idaho National Laboratory
ITER	latin for “the way”, the ITER International Project
JET	Joint European Torus
L	liter
LSC	liquid scintillation counter
min	minute
MTTR	mean time to repair
ORPS	Occurrence Reporting and Processing System
SPING	system particulate-iodine-noble gas
SRNL	Savannah River National Laboratory
STAR	Safety and Tritium Applied Research laboratory
T_2	tritium molecule
T_2O	tritium oxygen molecule
TPL	Tritium Process Laboratory
TSTA	Tritium Systems Test Assembly

SYMBOLS

β	beta radiation
γ	gamma radiation
D	total number of demands
λ	failure rate
n	total number of failures
T	total time period under study
χ^2	Chi-square statistical distribution

Radiation Protection Instrument Reliability and Maintainability Data

1. Introduction

This report is a collection of operating experiences for several types of radiation protection instruments. The instruments treated here include continuous air monitors used for room air monitoring to protect personnel in nuclear facilities, tritium air monitors used for the same task, stack monitors that are used to measure radioactivity being sent up the facility vent stack to the atmosphere, tritium bubblers used for the same task, tritium-in-water monitors for measuring tritium in effluent water from facilities, and hand-held survey meters used to assess radiation fields in nuclear facilities. The data presented include failure experiences, the calculated failure rates, and some repair times. Calibration is also briefly discussed, as well as battery lifetime for those units that rely on battery power.

2. Continuous Air Monitors

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 2-1. The allowable radionuclide concentration limits for personnel inhalation exposure in the U.S. are given in 10CFR20 and 10CFR8352 (ref 2-1, 2-2) 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.[2-3] The radiation detectors are typically Geiger-Müller counters or scintillation counters with photomultiplier tubes.

Figure 2-1. A typical first-generation continuous air monitor in a nuclear facility.

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. Some CAMs have been in use 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.[2-4] 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, which should ensure that the unit will draw air samples that are representative of the worker breathing air.[2-5,2-6] 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. A large facility will also have a small number 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 and those undergoing calibration. This chapter reviews CAM operating experiences and good practices and gives some reliability and maintainability values for these instruments.

2.1 CAM 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.[2-7] 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 2-1). Some reports were not included in this study because they described a CAM correctly responding to airborne contamination; the majority of which occurred during decommissioning and dismantlement activities. Other reports were not included because they referred to stack monitors rather than room air monitors. A third subset of the reports was not included 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 2-1, 29.7% of failures were electrical (including loss of power to the CAM 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% of the failures (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.[2-8] Failures of Geiger-Müller and photo-multiplier tubes were noted to be one of the widespread issues at the 55 plants that responded to the questionnaire. This is much different than the 8.2% of detector failures shown in Table 2-1. 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.[2-9] 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.

2.2 CAM 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 of operation 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 2-2.[2-10 to 2–13] Also, various Idaho National Laboratory (INL) records have been reviewed and provide enough data to support an order-of-magnitude failure rate estimates. 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. The geometric mean value of the "all modes" failure rates listed in Table 2-2 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 2-1. Continuous air monitor data from DOE events reported in ORPS.

Fault Category	Subcomponent fault 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

Table 2-1. Continuous air monitor data from DOE events reported in ORPS (continued).

Fault Category	Subcomponent or Error	Fault Count	CAM Alarmed the Fault[a]	CAM Did Not Alarm Fault
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
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 2-3 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.[2-8] 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.

As an example of the differences between sites, consider the data reported from the DOE Hanford site.[2-13] 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, three times 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 a failure roughly once per month. Using the data from Table 2-3 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 2-3 gives an average of 62 hr of technician time per CAM per year.

Table 2-2. 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	[2-10]
	Zero or maximum output	1.943E−06	2.693E−06	[2-10]
	No output	0.972E−06	1.347E−06	[2-10]
	No change of output with change of input	2.320E−06	3.216E−06	[2-10]
	Erratic output	3.161E−06	4.382E−06	[2-10]
	High output	1.595E−06	2.211E−06	[2-10]
	Low output	1.595E−06	2.211E−06	[2-10]
	Incipient failure	2.755E−06	3.819E−06	[2-10]
Radiation instrument	All modes	1.098E−05	3.310E−05	[2-11]
	Zero or maximum output	2.28E−06	6.86E−06	[2-11]
	No output	No value given		[2-11]
	No change of output with change of input	1.79E−06	5.39E−06	[2-11]
	Erratic output	2.42E−06	7.28E−06	[2-11]
	High output	1.21E−06	3.64E−06	[2-11]
	Low output	1.20E−06	3.64E−06	[2-11]
	Incipient failure	2.08E−06	6.29E−06	[2-11]
Radiation monitor	Drift	3.82E−05	1.98E−04	[2-12]
	Failure	3.80E−05	8.32E−05	[2-12]
CAM	All modes	1.1E−04	Not given	[2-13]

Table 2-3. 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	[2-7][b]
CAM unit repair in instrument shop with spare parts on hand	9 hours	INL data
	15.2 hours	[2-7][b]
CAM unit repair in instrument shop, requires ordering parts from vendor	10.5 days	INL data
	8 days	[2-7][b]
CAM mean time to repair	43.5 hours	[2-13]

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 here.

2.3 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 lose power or experience problems drawing air relatively frequently. Therefore, CAMs do 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 2-2. 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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3. Tritium Air Monitors

Personnel exposure monitoring is a fundamental safety precaution for a variety of airborne substances. Because future fusion experiments are tending toward use of kg quantities of tritium fuel, there is a chance that tritium can be released into the building atmosphere. Fixed point tritium air monitors are part of the protection scheme for personnel working with or near tritium fuel.

There are generally three failures of concern for tritium monitors: the failure to monitor, the failure to sound an alarm when required, and sounding a spurious alarm when no alarm condition exists. These failures are typically referred to as failure to operate or failure to function, failure to alarm on demand, and spurious alarm. All alarm systems have requirements or best practice standards that state the monitors must have high reliability, reliable actuation, and rare spurious actuations. Many standards address reliability on a qualitative level by stating that the monitoring system must be a simple design to promote high reliability, use low maintenance subcomponents, and avoid false alarms. This chapter addresses quantitative failure rates of tritium air monitors used in fusion research. These monitors may detect airborne tritium in elemental (T_2 or HT) or oxide (T_2O or HTO) form.

3.1 Tritium Air Monitor Experiences

To understand how tritium monitors are used in fusion facilities, we will look at monitor use in two facilities. At the Tritium Systems Test Assembly (TSTA) facility at Los Alamos National Laboratory, staff members used fixed tritium monitors for personnel protection and for building isolation in case of an airborne tritium release. These monitors were Kanne chamber type units that drew samples of room air into the chamber for readings of ion pairs created by beta decay. The TSTA monitors had three alarm levels. The first level was set at 1 derived air concentration (DAC) of tritiated water vapor (HTO) in air, or 20 $\mu Ci/m^3$ at that time. At that alarm, all non-essential personnel would promptly evacuate the area and designated personnel would quickly investigate the alarm to determine if the alarm was genuine. The second alarm level was set at 5 DAC (100 $\mu Ci/m^3$). At the second alarm level, any investigators would also evacuate but could return if they donned appropriate protective gear. The third level alarm was set for 500 DAC (10 mCi/m^3), which would sound an entire facility evacuation alarm and also isolate the TSTA building ventilation system.[3-1] The system never reached the highest alarm and only rarely reached the middle alarm in the years that TSTA operated. The TSTA monitors were operated at an artificial background setting of 5 $\mu Ci/m^3$, slightly above a true zero reading, so that if an artificially low or erratic reading was caused by abnormal instrument drift or other malfunctions it would be notable to the operators. Either a Ba-133 or Cs-137 check source was used for monitor checks.[3-1]

In the Safety and Tritium Applied Research (STAR) lab at the Idaho National Laboratory (INL), the two tritium monitors are the typical Kanne chamber type with room air drawn through the chamber. One of the monitors is shown in Figure 3-1. The STAR lab tritium air monitors have two alarm points: a low alarm at 15 $\mu Ci/m^3$ HTO (~0.8 DAC), which at STAR is 10 $\mu Ci/m^3$ HTO above the nominal background, and a high alarm at 100 $\mu Ci/m^3$ (~5 DAC). The U.S. Code of Federal Regulations presently defines the DAC for HTO vapor as 7E+05 Bq/m^3 (18.9 $\mu Ci/m^3$) of air.[3-2]

STAR personnel evacuate if the low level alarm sounds. Their procedure is to promptly evacuate the building, account for employees and visitors, and then use a cellular telephone or proceed to the nearest telephone in a nearby building to report the event to radiological control personnel and laboratory management.

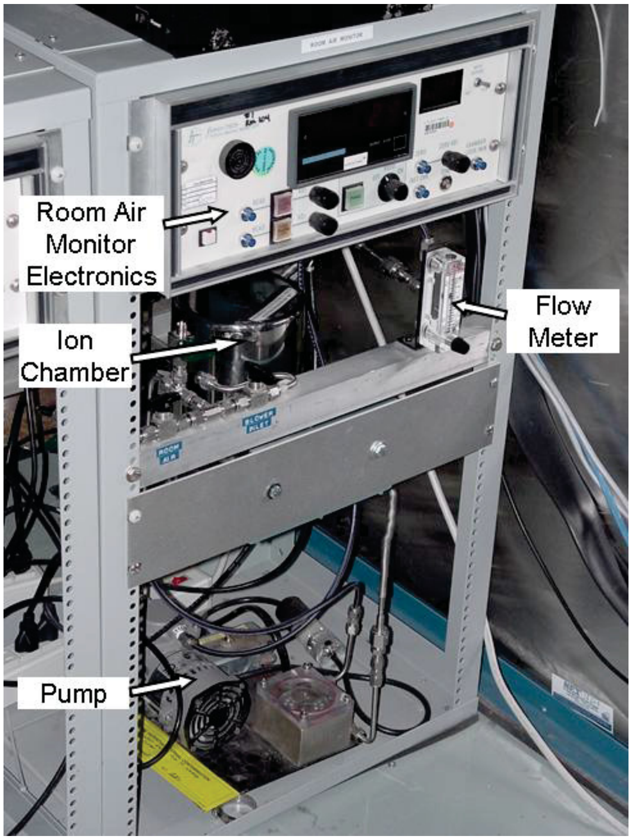

Figure 3-1. Tritium room air monitor at the INL STAR facility.

The STAR instruments have functioned well and the staff members have confidence in them. The monitors are given a daily inspection, a weekly source check with a Cs-137 source, and a detailed calibration every 3 years. The 3-year calibration time window is longer than the typical 6-month or 1-year interval. The long calibration time interval is allowed because of the strict tracking of check readings during the weekly source checks (within ±10% variance). If the instrument varies outside the ±10% range it must be recalibrated immediately at the health physics instrument lab. The procedure calls for transporting the electronics portion of the monitor to that lab to perform a bench test, which takes one day. If one of the two STAR monitors is being calibrated, the staff does not perform any major process evolutions at the facility. If there is cause for concern while one unit is gone then a radiological controls technician places a portable monitor unit in the room until the second STAR unit is returned. STAR does not have a spare tritium monitor on hand.

3.2 Tritium Air Monitor Data Assessment

The first mode of monitor failure described above, failure to operate, has been analyzed in several operating experience data sets.[3-1,3-3 to 3-6] These data are given in Table 3-1. The combined failure to function rate value from the three diverse data sets is estimated to be 3.5E−06/monitor-hr by geometric mean, and the upper bound is 4.7E−06/monitor-hr. The failure to operate rate includes the detector, electronics, internal power supply, air flow, contamination, and air pump faults but does not include loss of electric power to the monitor unit since the monitor cannot be held accountable for loss of power.

The second failure mode is the failure of a monitor to alarm on demand, where demand is defined as a valid, actual situation that requires the monitor to alarm. As mentioned, tritium is usually effectively confined and there are consequently very rare demands to these monitors. As a generality, most monitor units in fusion usage do not experience enough demands to obtain a statistically significant failure rate for this failure mode. The data examined here (listed in Table 3-2) are from tritium release tests and small operational releases at TSTA and STAR. All of the monitors addressed in these experiences are the most widely used Kanne chamber type, which draws room air into an ionization chamber by means of a small air pump.[3-7]

TSTA recorded a few operational release events.[3-1,3-8] Due to some research regarding tritium movement in room air, there have also been several small-mass tritium release tests performed at TSTA[3-9,3-10] and at the Tritium Process Laboratory (TPL) caisson facility at Tokai-mura operated by the Japan Atomic Energy Agency.[3-11 to 3-13] The TPL tests documented in the literature were highlights from 70 tests with tritium release levels between 0.26 and 26 GBq; the tritium monitor was out of order twice (did not function on demand) during that run of tests.[3-14]

Table 3-1. Tritium Air Monitor Hourly Failure Rates from Fusion Facilities

Facility	Failure Mode	Failure Rate (per hr)	Error Bound (per hr)	Reference
Tritium Process Laboratory (TPL)	Fail to function	See below[a]		[3-4]
TPL	Fail to function	1.1E−05	2.5E−05	[3-5]
TPL	Fail to function	5.9E−06	Not given	[3-6]
Joint European Torus (JET)	Erratic/no output	8.8E−07	4.2E−06	[3-3]
TSTA	Reads high or low	2.2E−06	1E−05	[3-1]
TSTA	All modes	4.3E−06	1.5E−05	[3-1]

[a] Using the failure count from [ref 3-4], 13 failures of the tritium air monitoring system, and 7 monitors [ref 3-6] operating for 19 years = 13 failures/[7 monitors × 19 yr × 8760 hr/yr], gives a result of 1.1E−05/monitor-hr as the point estimate failure rate. A standard error bound would be $[1.1\text{E}{-}05/(7 \text{ monitors} \times 19 \text{ yr} \times 8760 \text{ hr/yr})]^{0.5}$ or ±3E−06/monitor-hr. The TPL value appears to be 1.1E−05/hr. Combining this result by using a geometric mean with the JET “erratic/no output” and TSTA “all modes” values gives 3.5E−06/monitor-hr with an upper bound of 4.7E−06/monitor-hr.

The TSTA monitors were used in the large room tests to track tritium spread throughout the room and measure equilibration of the tritium concentration. In the smaller caisson tests at TPL, the monitor was used to measure the change in tritium concentration. The TPL caisson tests also used several “nude” ion chamber tritium monitors to detect tritium; those units were not included in the data set because they are a somewhat different instrument than the typical room air monitor that uses a pump and gas chamber. There have also been at least twelve very small leaks (< 1 mCi) of process tritium at the STAR laboratory. The STAR leak events have all been small amounts but have been more frequent than those at TSTA. The STAR events alone are not sufficient for statistical evaluation, but these events do contribute to a combined data set. The small releases at STAR produced between 15 and 80 $\mu\text{Ci/m}^3$ concentration ranges in room air, which was sufficient to alarm a monitor. In these events, the challenged monitor functioned on demand, performing as intended. It is noted that the data in Table 3-2 constitute only a small set of data for a small number of tritium monitors but these are valid data of demands to monitors from actual tritium release conditions and the data can be used to estimate the monitor failure rate for failing to alarm on demand.

A statistical approach for calculating failure rates was outlined in Ref. 3-1, and is used here for demand failure rates. The point estimate failure rate is the total number of failures on demand divided by the total number of demands for the data given in Table 3-2.

λ = (total failure count)/(total demand count) (1)

The upper bound failure rate[3-1] would be

$\lambda = \chi^2(0.95,2(n+1))/2D$ (2)

where

n = total failure count

D = total demand count.

Table 3-2. Monitor Operational Data from Small Tritium Releases

Event/Test Designator	Tritium Released (mCi)	Number of Monitors	Number of Releases[a]	Reference
1	≈ 60 est.	8	1	[3-1]
2	≈ 60 est.	8	1	[3-1]
3	145	8	1	[3-8]
4	1,000	8	3	[3-9]
5	1,000	8	2	[3-10]
6	7	1	1	[3-11][a]
7	7.5	1	1	[3-12]
8	70	1	4	[3-13]
9	7–700	1	62	[3-14][b]
10	< 1	1	13	INL STAR lab over ≈ 12 years
Release event totals 8(1)+8(1)+8(1)+8(3)+8(2)+1(1)+1(1)+1(4)+1(62)+1(13) = 145 monitor-demands				
a. Note: There were six “nude” ion chambers on the caisson as well but those units were not included here. b. There were two faults in the monitor over 10 years. In the other listed release events, there were no monitor failures on demand.				

The calculated chi-square distribution value for n=2 is 12.592 for the 95% upper bound.[3-15] Using this value and the demand count data from Table 3-2, the tritium air monitor average failure rate for failure to alarm on demand is (2/145) = 1.38E−02/demand with a 95% upper bound of (12.592/2(145)) = 4.3E−02/demand.

The third failure mode, spurious alarms, has been known to occur with tritium monitors like other types of fixed monitors, but it is a somewhat rare event. For example, STAR experience is that a false alarm occurs at the facility perhaps once every 3 years, or 0.33/yr. Therefore, each of the two monitors has a spurious tritium alarm rate on the order of 0.17/yr. This appears to be a typical frequency estimate for a tritium research facility using a set of tritium monitors. TSTA spurious alarms were also rare.[3-1]

The spurious alarm rate can vary with the age of the monitor, the age of the facility, the quantity of tritium used in the facility, the monitor manufacturer or brand name, and monitor recalibration frequency. There can be other factors for false alarms as well, including the monitor sensing radon gas rather than tritium,[3-16] the presence of foreign vapors that cause the monitor to alarm (such as welding fumes),[3-1] or the monitor sensing a non-tritium beta-gamma emitter.

The spurious alarm failure mode has not been investigated in any detail because such alarms (and the room or facility evacuations they may cause) are more of a nuisance and an operating cost burden than a safety issue—if the spurious alarms are infrequent enough so the staff does not become inured to the tritium alarms. In regard to human behavior when alarms sound, Proulx[3-17] states that specialists in fire protection tend to agree that more than three nuisance or false alarms in a year undermine credibility of fire alarm systems and people tend to ignore the alarms. Certainly there is a higher level of professionalism in nuclear facility operations than in residential or public buildings, but if false alarms occurred with high frequency then workers may suspect a false alarm first and may not evacuate very quickly. The spurious alarm frequency noted at STAR is sufficiently low, and much lower than the valid alarm frequency from operational releases, so there is no concern about personnel responding correctly to an alarm.

3.3 Comparison of Results

The military specification for reliability of fixed and portable tritium monitors states that the monitors shall have a mean-time between-failures of 3,000 hours or more (a failure rate of 3.3E−04/hr or lower), and a mean corrective maintenance time to repair a monitor not exceeding 30 minutes (a mean time to repair of 0.5 hr).[3-18] All values from the failure to function data given in Table 3-1 surpass that specification. The military specification does not give a value for failure to alarm on demand. Therefore, to check the validity of the value calculated here (1.38E−02/demand), reliability values for other types of alarms were sought for comparison. Some monitor demand performance data were located for smoke detection systems used for fire protection in nuclear power plants.[3-19] The failure of a smoke detector to alarm when challenged with a valid fire and smoke condition varied from 1E−03/demand and even as low as 1E−05/demand for nuclear power station smoke detection systems. Because smoke detection is an engineered system to protect human health and safety, these performance values are believed to be generally comparable to the tritium air monitor results. The nuclear power plant smoke detection system not only sounds a local alarm for personnel evacuation, but it will also signal for ventilation shut down, smoke control system actuation (e.g., close smoke dampers), and actuation of water flow to “dry pipe” sprinkler systems if such systems are used in the facility. Thus, the nuclear power plant smoke detection system has similar ventilation control functions to some tritium air monitoring systems. The upper end of the nuclear fission power plant rate was about fourteen times less than the tritium monitor results. Because of our small data set and the general believe that tritium monitors are reliable, it is possible that with more tritium release tests the calculated tritium air monitor failure to alarm on demand value would decrease further and be more comparable to the upper end of the nuclear power plant smoke detection system value of 1E−03/demand.

Another type of monitor that is important for personnel safety is a nuclear criticality alarm system. A literature search revealed little data about the reliability of these detectors, but a recent purchase contract specification cited an acceptable range for failure to alarm on demand of 1E−02 to 1E−03/demand and a spurious alarm rate of < 0.1 event/year.[3-20] A vendor study gave a failure to alarm on demand value of 1.7E−03/demand with a 1-year test interval, and 1.3E−04/demand rate for a 1-month test interval.[3-21] The spurious alarm frequency for a criticality alarm system was given as 0.05/year. Criticality alarm systems are intended for personnel and public safety; a criticality alarm not only signals for a quick evacuation of workers to evade prompt radiation exposure, but also actuates a lockdown of facility ventilation and de-energizes processes so there are no activated material releases to the environment. For the criticality alarm systems, apparently a 1E−02 to 1E−03/demand failure rate range is considered adequate for personnel safety when the rarity of a nuclear criticality event is taken into account. The tritium monitor value of 1.39−02/demand calculated here is just outside the 1E−02 to 1E−04 range given for a criticality alarm system. This is a surprisingly good result given that the tritium monitor data are sparse. However, longer operation times may result in continued correct operation and lower demand failure rates. The STAR tritium monitor spurious alarm rate was estimated to be greater than that of criticality monitors, which are not particularly prone to false alarms.

3.4 Conclusions

Fixed monitoring for airborne tritium is necessary for personnel safety. Examination of monitor failure rates for failing to operate has yielded a combined value of 3.5E−06/monitor-hr with an upper bound of 4.7E−06/monitor-hr. This is a factor of ≈ 94 below the published quantitative reliability level of 3.3E−04/monitor-hr stated in a military standard. The issue of monitors sounding a valid alarm has also been examined. The tritium release tests that have been conducted in fusion tritium facilities not only provided valuable information about tritium movement and behavior within buildings and enclosures, but have also produced a set of demand trials that exercised the tritium monitors used in these facilities. Two failures occurred in this compilation of tests and operational releases. The test data are recognized to be sparse, but the data described in Table 3-2 constitute a larger data set than has been readily available for these monitors in the past. Statistical treatment of these test data gave a failure to alarm on demand failure rate of ~1.4E−02/demand, with an upper bound failure rate of 4.3E−02/demand. In comparison to other types of monitors having the same types of requirements to provide for personnel safety, tritium air monitors compare poorly (≈ 14 times higher failure rate) to nuclear power plant smoke detection monitor systems, and compare favorably (1.4 times higher failure rate) with nuclear criticality alarm systems. This was a good result considering the small data set. It is possible that additional tritium monitor operation may yield lower demand failure rates than the 1.4E−02/demand calculated here. Monitors sounding spurious or unwanted alarms has not been treated in detail but operating experiences indicate the value should be on the order of 0.1 or 0.2/monitor-yr, which was greater than cited values for other monitors but is still a low value.

3.5 References

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4. Stack Monitors

A stack monitor is a device used to measure the radioactivity in samples of effluent air being exhausted from the facility vent stack to the environment. A representative stack gas effluent monitor is shown in Figure 4-1.[4-1] Effluent monitoring design requirements are given by the US Department of Energy (DOE) and other federal regulations.[4-2 to 4-4] It is required that emissions of radionuclides to the ambient air from DOE facilities shall not exceed amounts that would cause any member of the public to receive an effective dose of 0.1 mSv/year (10 mrem/year).[4-4] The stack monitors sample gaseous effluents to indicate if that limit is being approached. The sampling and monitoring systems must provide adequate and accurate measurements under normal operations, anticipated operational occurrences, and any accident conditions. Monitoring systems should be calibrated at least annually. Stack monitors should have central readouts and alarm panels which are accessible after an accident to allow evaluation of conditions. Radiation monitoring, alarm, and warning systems that must function during a loss of power should have emergency power, with the type and quality based on the safety classification of the monitor. A long-standing design principle of these monitors is to have a redundant backup unit in place so that if the primary unit experiences a fault then a redundant unit can be activated to ensure continued monitoring of the stack gases.[4-5] Most fission-related facilities refer to these monitors as system particulate-iodine-noble gas (SPING) monitors. The SPING monitor contains separate detector channels tailored to read specific energies of radioactive decay from particulates, iodine, and noble gases. Generally, sample air is drawn at a modest flow rate (e.g., 80 liters/s) and is routed from the stack to the isokinetic samplers and to the monitor channels located somewhere near the base of the stack. The sample line is usually kept short (e.g., a few meters) to preclude plateout in the line and to maintain sufficiently high velocity flow since the sample air flow through a filter paper provides a record of particulate releases even if the monitor's sample pump has failed.[4-3] A fusion facility is expected to focus on particulates and activated air as the primary effluents to be monitored with this type of equipment. In fusion facilities that handle tritium, one detector channel of the stack monitor can be devoted to this radionuclide. Often in the US, facilities use an ethylene glycol bubbler system to measure low levels of tritium gas in samples of effluent air being stacked. Tritium bubblers are addressed separately in a later chapter.

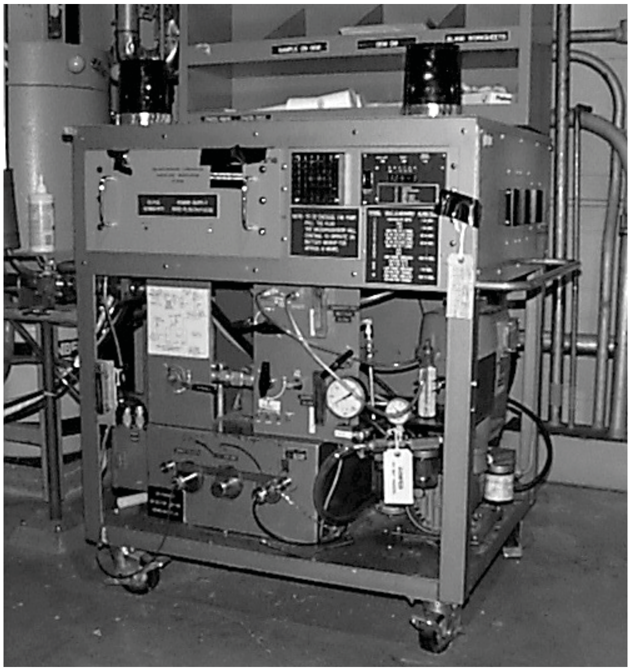

Figure 4-1. A typical stack gas effluent monitor (reprinted with permission from ref. 4-1)

Some stack monitors use the same equipment as the continuous air monitor (CAM) that provides for worker breathing air protection within the facility. In that type of unit, particulate collection on filter paper is used to measure the activity of any airborne material.4-6 Radiation detectors in CAMs are typically Geiger-Müller counters. Some stack monitor channels use these, while other stack monitors can be more sophisticated than CAMs, using scintillation detectors, ionization chambers, or other radiation detection instruments.

4.1 Stack Monitor Experience Data

A search of the DOE ORPS database narrative descriptions for "stack monitor" returned 360 ORPS reports (see Table 4-1). Some reports were not included in this study because they described a stack gas effluent monitor correctly responding to airborne radioactive gas or particulate. Other reports were excluded because they referred to room air monitor issues rather than stack monitor issues. A third subset of the reports was excluded because a stack monitor was mentioned but the report addressed some other, unrelated equipment failures. These exclusions left 263 reports of faults attributable to stack monitors. As derived from Table 4-1, 35% of failures were electrical (including loss of power and power supply problems and electrical noise), 16% of the failures were mechanical (mainly in the air pumping portion of the units – reference 4-3 cites that vacuum pumps must be easy to replace), 19% resulted from human errors, 21% were radiation instrumentation faults, and 9% were environment-related faults.

One interesting issue is the number of stack monitor failures where the monitor did not annunciate a fault or otherwise issue some type of trouble alarm. In human-error-caused failures, the monitor did not annunciate in 33/51 or 64.7% of the events. In 18/40 or 45% of the mechanical faults and 18/92 or 19.6% of the electrical faults, the affected monitors did not issue a trouble alarm. Facility personnel learned of most of these failures from testing performed each day or each shift. Therefore, the periodic (daily or more frequently) inspections that stack monitors receive is warranted and is a best practice for this type of instrument, at least for the presently used level of technology. 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.

One notable difference between the CAM data considered above and these stack monitor data is that human errors by non-monitor workers are greatly reduced for the stack monitors. Most CAMs are positioned to monitor room air and are generally accessible to many workers, while the stack monitors are generally located near the base of a facility vent stack and are typically shielded so that they register only radioactivity in the stack gases. There may also be shielding to protect stack monitor electronics from exposure to accident doses, which further segregates the stack monitors from facility workers. Thus, stack monitors are more isolated from workers who do not test or maintain these monitors, so human errors are reduced.

4.2 Stack Monitor Reliability and Maintainability Data

The ORPS reports describe the failure modes of stack monitor units but do not give enough information on units in use and the time periods over which these units have operated to calculate failure rates. Instead, the literature was searched for published failure rate data on stack monitors. One recent document found on this topic was that authored by Grigsby.[4-7] Also, various INL records have been reviewed and provide enough data to support an order-of-magnitude estimate of the failure rate. The stack monitor data showed 15 failures requiring repair in 12 years, which gives a failure rate of 15/(12 y)(8760 h/y) = 1.4E-04/hour. It should be noted that this is a single unit failure rate value; the stack gases were always monitored by a redundant unit in case of a failure in the primary unit. Grigsby reported a failure rate of 1.1E-04/hour for a set of forty continuous air monitors used as stack gas monitors over about two years. Grigsby's result has good agreement with the INL cursory value, and so a representative order-of-magnitude estimate of the "all modes" failure is 1E−04/unit-hr based on the two data sets. The INL data also recorded false alarms, which were 5.5/year or roughly one event every other month. There were no

INL events of failure to alarm when required by airborne activity. There have been too few events of high airborne activity challenging the INL stack monitors, so any statistical estimate of failure to alarm on demand is not meaningful.

Considering repair, Grigsby[4-7] gave a mean time to repair (MTTR) value for stack monitors of 43.5 hours. At the INL, the average stack monitor repair time with spare parts on hand was 17.5 hours; without spare parts on hand, the average was 160 hours, meaning parts procurement time drives up the downtime. Calculating the overall MTTR from INL data gives 49.1 hours, which is only 13% difference from Grigsby's value. This result is a good comparison when one considers the variability often seen in maintainability data values. Table 4-2 gives some other maintenance time data for stack monitors.

4.3 Conclusions

The stack monitor experiences show that the highest percentage of failures is in power interference and in electronic noise, followed by radiation instrument faults and human errors, then failures in the mechanical portion of these monitors. The current approach in the DOE Complex is to have a redundant unit to provide continuous monitoring while a faulted unit is being repaired. Daily operability checks and weekly functional tests are warranted because continuously operating stack monitors, 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 monitor unit, so daily visits keep the units available to perform their tasks. Daily visits and even checkup visits each during 8-hour shift are a best practice for stack monitor operability.

The literature search for stack monitor failure rates yielded only one valuable result. Assessing the "all modes" failure rates from the literature and INL data gave a representative, order-of-magnitude failure rate of 1E−04/unit-hr. This value is reasonable to apply to stack monitor units if no component-specific, site-specific, or otherwise better data sets are available.

The failure modes, rates and repair times are useful for facility operations to assure that stack monitors are designed to operate well by negating failure modes, and by providing redundant units. The repair time data for these monitors can be used to estimate the number of radiological control technicians needed to support the stack monitors for routine work and repair work.

Table 4-1. Stack monitor data from DOE events reported in ORPS.

Fault Category	Subcomponent or error	CAM Alarmed the Fault	CAM Did Not Alarm
Mechanical			
Maintenance	End of life aged parts	3	4
Maintenance	Filter	1	4
Maintenance	Dirt interference	2	1
Mechanical part	Pressure transmitter	5	1
Mechanical part	Part failure- fittings, belt	2	1
Mechanical part	Vacuum pump	11	8
Electrical			
Electronic	Capacitor, diode, resistor	5	2
Electrical mechanics	Wiring or fuse problem	4	5
Electrical mechanics	Electronic module problem	6	2
Electrical mechanics	Unknown problem	1	2
Electrical noise	Noise interference	40	1
Electrical settings	Alarm set point	4	3
Power	Power interference	12	1
Power	Relay switch	2	2
Environmental			
Design	Environmental fault-condensation or other	0	2
Design	Chiller shut down interference	3	0
Object	Foreign Material Interference	1	0
Weather related	Lightning	4	0
Weather related	Rain/Water	3	0
Weather related	Wind	1	0
Weather related	Temperature High/Low	7	1
Radiation Instrumentation			
Exterior instrument part	Chart erratic readings	3	5
Exterior instrument part	Chart paper problem	0	2
Exterior instrument part	Check source	4	2
Internal instrument part	Mylar film torn or damaged	1	4
Internal instrument part	Keithley amplifier	0	5
Internal instrument part	Meter	3	3
Internal instrument part	Unknown broken part	1	0
Internal instrument part	Geiger Muller tube	17	5
Human Error			
CAM worker power	Wiring wrong	0	2
Non CAM worker power	Interference of power	6	3
CAM worker	Calibration setting incorrect	1	12
CAM worker	Calibration not calibrated	0	2
CAM worker	Calibration source check problem	0	2
CAM worker	Physical interference bump/wrong movement	3	1
CAM worker	Physical interference door ajar, valve wrong	5	5
CAM worker	Physical Interference too clean	0	1
CAM worker	Chart paper left empty or filled wrong	1	4
CAM worker	Water reservoir not filled	1	0
CAM worker	Physical interference air conditioner	1	0
CAM worker	Physical interference not enough insulation used	0	1

Table 4-2. Maintenance and repair times for stack monitors

Activity	Average Time	Source
Technician calibrates one of the SPING monitor channels	15 minutes	INL data
Technician performs SPING weekly filter change	15 minutes	INL data
Technician calibrates a SPING instrumentation logic channel to the control room	2.5 hours	INL data
Technician replaces SPING Geiger-Müller tube	2.0 hours	INL data
	1.9 hours	[4-7][b]
SPING general repairs with spare parts on hand	17.5 hours	INL data
	15.2 hours	[4-7][b]
SPING general repairs without spare parts on hand, requires ordering parts from vendor	160 hours	INL data
	8 days	[4-7][b]
SPING overall mean time to repair	49.1 hours	INL data

a. Technician activities do not include travel time to the monitor unit.
b. A few of the ORPS reports gave repair times and these times were averaged for presentation here.

4.4 References

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5. Tritium Bubblers

A tritium bubbler is a tritium collection monitor that can discriminate between elemental (HT or T_2) and oxide (T_2O or HTO) forms of tritium vapor in air. A bubbler can be used to sample workplace air or stack effluent gas. As a stack monitor, a tritium bubbler is an important piece of equipment for protection of the environment. All US Department of Energy (DOE) facilities are required to monitor their airborne releases of radionuclides to show compliance with the 0.1 mSv/a (10 mrem/year) dose limit to the public.[5-1] Bubblers do not provide an in-situ measurement, they are used to sample the air stream for a fixed period of time and then the bubbler material (either water, ethylene glycol, or silica gel) is analyzed for its tritium content. Differentiating between elemental and oxide form is necessary due to the difference in biological hazard potential of these two forms of tritium. For this reason a bubbler will have two stages – the first stage samples the inlet air stream directly to absorb HTO. Then the air stream is heated over a palladium catalyst to oxidize any HT in the air stream. That gas is sent through a second set of bubbler vials to absorb the newly-created HTO.[5-2]

There are several types of tritium stack monitors available. For many years the US DOE practice was to use a gas sample port and route a small portion of the stack gas (at, for example, 100 cc/minute) to a moisture absorbing gel. The gel would absorb virtually all the HTO vapor and if the exiting sample gas was heated with a catalyst then any elemental tritium would be converted to HTO and another quantity of gel would absorb that vapor. However, this approach tended to be labor-intensive, since all of the gel had to be removed and placed in an ion chamber to survey the tritium, and the tritiated gel comprised a significant mass for waste disposal.[5-3] In the 1970's, the bubbler-catalyst-bubbler approach was used for tritium capture. This method used only a few ml of bubbler liquid, which was easily transferred to a scintillation counter. The bubbler liquid was less volume than the gel, which reduced the amount of waste for disposal. The bubbler offered good efficiency over a wide range of tritium concentrations, so the monitor would function well in normal and accident situations. Today the tritium bubbler is a standard choice for stack monitoring at tritium facilities.

There is generally one failure of concern for bubblers: the failure to sample. This failure is typically referred to as failure to operate or failure to function. This chapter addresses qualitative failure modes of tritium bubblers and gives a tritium bubbler 'failure to operate' failure rate based on operating experience of a tritium bubbler used in fusion research.

5.1 Bubbler Operating Experiences

To understand how tritium bubbler stack monitors are used in fusion facilities, we will examine the operations of a tritium bubbler used at the Safety and Tritium Applied Research (STAR) facility at the INL. This bubbler is shown in Figure 5-1. The bubbler is typically connected to a gas sample collection line in the facility vent stack, taking a stack air sample at 100 cc/minute (0.006 m^3/h) from the typical stack air flow of 3200 m^3/h. STAR stack air flow has on the order of perhaps 10 mCi of tritium at a given time, so the bubbler sees only a tiny fraction of that amount. The sample air is filtered for dust and particulates to prevent intrusion in the bubbler liquid. The bubbler senses air mass flow rate and pressure. The six white plastic vials shown on the right side of the front of the monitor in Figure 5-1 are each filled with 10 ml of ethylene glycol ($C_2H_6O_2$), which absorbs tritiated moisture from the air stream. The vials are changed out weekly at STAR and seven vials (the 6 process vials plus a capped off 'control' vial) are taken to a radiation counting lab for liquid scintillation counting of the tritium captured in the ethylene glycol. In the bubbler, the first three vials of ethylene glycol (the upper row in Figure 5-1) absorb moisture from the sample air flow, then the air is routed to a small chamber within the bubbler unit. The small chamber has a heated (475°C) palladium catalyst. The catalyst oxidizes any HT and any tritiated organic molecules to create HTO. Then the treated air passes through the second set of three vials. Thus, the first three vials capture the original HTO concentration in the air and the second three vials that capture newly created HTO give the original HT concentration in the air. Like most bubblers, the STAR bubbler for tritium effluents does not possess real-time alarm capability. Effluent tritium release data is based on the facility exhaust flow rate and weekly sample counting. The sample count timing can be adjusted if the staff foresees changes to the experiment activity or increased tritium handling, but with the low releases at STAR and consistent operations schedules, weekly vial changeout is acceptable. This method provides the necessary data to calculate the STAR tritium stack releases for the INL annual radionuclide emissions report, which is submitted to the local government and the US DOE.

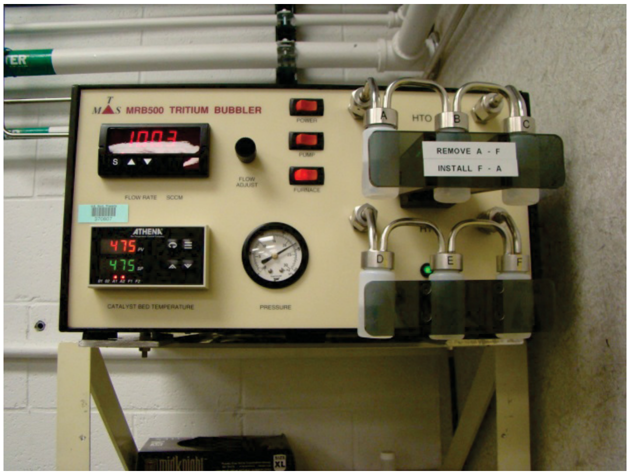

Figure 5-1. Tritium bubbler stack monitor at the INL STAR laboratory.

The STAR tritium bubbler has functioned well. There have not been any off-normal events with this unit over the past 9.5 years. The monitor is given a brief (~1 minute), daily visual inspection to verify the bubbler instrument readings show it is operating properly with correct values of air flow and catalyst temperature. The weekly vial changeout takes approximately 6 minutes at the monitor unit for all six vials. This includes unscrewing and capping each vial, then installing a fresh vial. Preparing the new set of vials (filling with ethylene glycol and weighing) requires a few additional minutes. Bubbler downtime for vial changeout is (6 minutes/week)(52 weeks/year) = 312 minutes or 5.2 hours. A monthly test of the sample air flow is performed in ~20 minutes with a bubble tube to measure the air flow rate, which is compared to the flow rate reported by the unit's integral mass flow controller. The staff regularly replaces the graphite vanes of the air flow dry vane pump. The procedure is to take tritium smear samples before starting the task, then measure the air flow rate before air pump maintenance. Next, the unit is de-powered, isolated, and the air pump is removed. The pump casing is opened (more tritium smear samples are taken), and the old graphite vanes are removed. Then the new vanes are installed and the pump placed back in the unit. The unit is unisolated, energized and sample air flow is measured again. This vane replacement task, performed by one person, requires about 2 hours, plus an additional 1.5 hours for the catalyst bed to come back up to temperature after the unit is re-energized. The vanes are replaced every year. Vial and vane replacement is about 8 hours of bubbler isolation each year. The air filters are examined annually. STAR does not have a spare tritium bubbler, so the unit downtime means the stack air was not sampled during the unit outage period. However, the outages are short time durations and are planned so that bubbler maintenance is not performed during experiment campaigns or when tritium is being actively handled in STAR.

Since the STAR monitor constitutes a small data set on operating experiences, the U.S. DOE Occurrence Reporting and Processing System (ORPS) database of equipment faults and human errors at DOE facilities was searched.[5-4] The reporting period searched, 1990 to the end of 2009, encompassed dozens of tritium bubblers across the DOE Complex. A search of ORPS narrative descriptions for "bubbler" returned 143 ORPS reports (see Table 5-1). Seventy-eight reports were excluded because they described different types of bubblers, not bubbler samplers. Forty-one of the reports described tritium bubblers operating as designed, often as a backup to other types of tritium monitors (e.g., ion chamber units). Twenty-four of the reports described faults with tritium bubblers. As derived from Table 5-1, 4/24 or 16.7% of failures were electrical (including loss of power and circuit breaker trips), 8/24 or 33.3% were human errors (including one event where the bubbler air line was disconnected in an act of malicious mischief), and 12/24 or 50% of the failures were mechanical (mainly in the air pumping portion of the units, and a few sample vial faults). The ORPS reports illustrate the failures and failure modes of bubblers, but there is insufficient data on numbers of bubblers operating and their operating times to calculate failure rate values from ORPS data.

As well as the ORPS search, radiation protection literature was surveyed for discussions of tritium bubbler operating experiences. Sheehan[5-5] discussed early operating experiences with bubblers at the US Mound facility in Ohio. The early units used metal bellows pumps that forced sample air through the unit rather than drawing air under negative pressure through the unit. Newer units use centrifugal air pumps (i.e., vane pumps) that draw air through the unit rather than bellows pumps. This tends to preclude the positive pressure effect of reverse air flow during bubbler vial changeouts. However, newer units have an air flow isolation valve to use during vial changeouts. The early units also required a change of the seal on the bubbler vials. Mound researchers switched to o-ring seals to preclude air leakage out of the bubbler vial seals. Munyon[5-3] discussed a few experiences with facility-built (rather than commercially purchased) units. An important issue was the so-called 'memory effect' of the bubbler. This means residual internal contamination in the bubbler tubing and catalyst can cause higher than true readings when the actual tritium concentration in the sample air is very low. Munyon described a test where a bubbler was purged with clean air for a week after routine operations. The bubbler vials ahead of the catalyst collected 965 Bq (0.026 μCi) of tritium while under a week of normal conditions they would have collected 130,000 Bq (3.51 μCi). The bubbler vials situated after the catalyst collected 14 kBq (0.38 μCi) of tritium, while normally they would have collected approximately 300 kBq (8.1 μCi). Thus, the residual tritium in the bubbler tubing was roughly 0.7% of the normal collection, and the residual tritium in the catalyst was about 4.6% of normal collection. Periodic flushing with clean air (with the use of a portable bubbler to monitor the effluent) is recommended to reduce the memory effect. The JET experiment also reported an issue with tritium absorption in long plastic tubing of air sample lines, which resulted in artificially low tritium concentration readings. The JET staff modified the long sample lines that had a small flow rate to take flow locally from a faster flowing air sampling loop.[5-6]

No information on bubbler operational reliability from other facilities could be obtained. Most fusion facilities use bubblers in combination with other types of tritium monitors to closely track the tritium releases from the facility. For example, the JET machine used 20 on-line ion-chambers, 3 discriminating HT/HTO samplers, and several tritium bubblers for workplace air monitoring. This combination is believed to be used to obtain the benefits of direct readings by the ion chambers and the longer-term 'time period' readings from bubbler vial analysis. For facility vent stack readings, JET used on-line ion-chambers and integrating HT/HTO silica gel based samplers.[5-7]

Table 5-1. ORPS Report Results for Tritium Bubblers

Type of Fault Reported	Fault Count	Description of Faults
Electrical problem	4	Circuit breaker worn insulation; power supply board failure; power spikes led to circuit breaker trip; sustained facility power outage that led to depletion of backup batteries
Human errors	8	Technician mispositioned a valve during sample vial changeout (isolating the bubbler); worker bumped bubbler causing sample vial misalignment and gas leakage; in two events technicians did not close the fill hole correctly so gas escaped to the room; a technician contaminated the ethylene glycol so that it foamed over and deactivated the catalyst; the glycol level was too low in the vials; a worker accidentally activated the bubbler on/off switch. In one isolated case of malicious mischief, air lines to the bubbler were found intentionally disconnected while the bubbler was in operation.
Mechanical problem	12	There were five events of worn out pumps or pump vanes; one pump failure due to pump overheating caused by restricted air flow; one event of a broken air line to the bubbler; and three events of worn out valves. There were two events of plastic vial problems - one was a manufacturing defect that resulted in a hole in the plastic vial and the other was a deteriorated vial seal to the bubbler.

5.2 Bubbler Reliablity and Maintenance Assessment

Despite the importance of tritium bubblers used in stack monitoring, no failure rate data values were found in an extensive literature search. The STAR unit discussed above is just one unit with limited operating experience from 2004 to mid-2013, but it does set a point estimate failure rate for failure to function with no failures to sample stack air in 8.5 years. The US Nuclear Regulatory Commission approach to failure rate estimation with no failure events[5-7] is $\lambda=0.5/T$. Therefore, this monitor would have a zero-failures approximate failure rate of $\lambda_{avg}=0.5/T$ where T is the total unit operating time. The time T is the entire year minus 8 hours for maintenance, or 8760-8 = 8752 operating hours per year. $\lambda_{avg}=0.5/[(8.5\ y)(8752\ h/y)]$ or 6.7E-06/h, which rounds up to 7E-06/h. The 95% upper bound failure rate would be a Chi-square distribution[5-8], $\lambda_{95\%}=(\chi^2(0.95,2n+2))/2T$, where n=number of failures. $\chi^2(0.95,2)=5.99$, so $\lambda_{95\%}= (5.99)/(2)(8.5\ y)(8752\ h/y)$ or an upper bound failure rate of 4E-05/h. The 'failure to operate' failure rate includes all monitor failures (air pump faults, heater faults, instrumentation faults) but does not include loss of electric power to the monitor unit. The bubbler is not a direct-reading instrument and it has no radiation alarm function.

The bubbler is a sample collector; a liquid scintillation counter is used to periodically measure the tritium concentration in the ethylene glycol in the bubbler vials. Therefore, there are no radiological 'failure to alarm on demand' or 'spurious alarm' failure modes for this type of device. The bubbler is a simpler type of monitor with fewer parts than other monitors such as continuous air monitors or tritium air monitors. A fundamental reliability concept is that simpler is more reliable, parts not included in the design cannot cause a failure.

The ORPS data showed that several facilities have adopted a practice of replacing the air pump (also referred to as a vacuum pump) on the bubbler unit to improve the bubbler reliability in sampling. Some facilities replace the pump at 24 to 34 months of service. The STAR facility also replaces the air pump graphite vanes annually, and has replaced the entire pump unit once in 6.5 years. This planned replacement period keeps the bubbler units from experiencing loss of sampling by following a pre-selected replacement time interval so that the air pump does not wear out and fail in service. Review of a failure rate compilation for small vacuum/pneumatic pumps[5-9] shows that 3E-05/h is a reasonable value for these small units, so replacing units at 24 months gives a failure probability of (3E-05/h)(8760 h/y)(2y) = 0.53 and at 34 months gives a 74% failure probability. Thus, the air pump units tend to be replaced when they are at failure probabilities of greater than 50%, which illustrates the tradeoff between economics of replacement parts and the need for continued bubbler functionality.

The INL STAR bubbler experience has yielded an average failure rate of ~7E-06/h. Other, more complex tritium monitors have been investigated in prior chapters, and have shown failure rates on the order of 3.5E-06/h, which is factor of 2 less than the bubbler failure rate. It is counter-intuitive that the more complicated tritium ion chamber type monitor with multiple functions and alarms would exhibit greater reliability than the simpler tritium bubbler unit. Therefore, it is possible that if the experiences of a larger population of bubblers were studied, a lower failure rate might be obtained for bubblers. The individual STAR bubbler experience that gave 7E-06/h is considered to be an upper bound value for bubblers in general until further data is found on bubbler operating experience.

5.3 Conclusions

The ORPS data of field experiences of tritium bubblers showed that these units serve as reliable sampling systems for stack monitoring in tritium facilities. Examination of the failure rate for a bubbler failing to operate has yielded an operating experience value of 7E-06/h with a 95% upper bound of 4E-05/h. This failure rate is based on the experiences of just one unit over 8.5 years of operation, which is a very small sample. If the operating experiences of a larger set of bubblers were examined, perhaps a lower failure rate would be obtained. Until more data on tritium bubblers can be obtained and analyzed, the 7E-06/h failure rate will be assumed to be an upper bound failure rate for tritium bubblers. It was noted that the bubbler operating experiences reported in ORPS showed that the majority of faults are in the mechanical parts, the air pump and valves. Some facilities replace the bubbler air pumps in routine time intervals of 24 to 34 months to prevent air pump failures in service. This is a good practice that gives the bubblers higher operating time in a given year. This chapter also gave the typical maintenance times for a vent stack bubbler unit, including vial changeout (1 minute/vial), air flow meter calibration (20 minutes), and air pump vane replacement (about 3.5 hours total time).

5.4 References

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6. Tritium in Water Monitors

One of the motives to pursue magnetic fusion energy is the belief that a fusion power plant will have less environmental impact than present forms of electricity production. Since the first-generation fusion power plants of the future will use tritium fuel, monitoring to show that tritium is not being released to the environment is an important aspect of fusion facility operations. The nations involved in fusion research all have limits for radionuclides released into water, including tritium. In the US, the Environmental Protection Agency has a limit for tritium of 20,000 pCi/liter of drinking water, which is stated to give a dose of 0.04 mSv/year (4 mrem/y) to an individual drinking such water.[6-1] The US Nuclear Regulatory Commission has a goal value of 0.03 mSv/year for the dose from fission power plant liquid effluents[6-2] and a tritium average monthly release into sewerage of 0.01 μCi/ml.[6-3] Monitoring is essential to verify that a facility has complied with such limits.

Environmental responsibility and observing regulations on tritium are important, but it is also noted that tritium releases can be politically sensitive events. In the US, one laboratory had a chronic but low-level release of tritium for many years in the 1980's and 1990's. When the level at the release point increased to twice the drinking water standard, the firm operating the laboratory was dismissed and the facility where the leak originated was closed.[6-4] More recently, tritium releases from US fission power plants have been a concern for environmental stewardship.[6-5] Therefore, monitoring for tritium releases is an issue of not only regulatory but also political importance for any facility that handles tritium.

One of the best known and most used methods of verifying compliance with tritium effluent water release limits is to take periodic grab samples of effluent water and analyze the water samples in a liquid scintillation counter (LSC).[6-6] The LSC is well suited to detect the low energy beta particles emitted by tritium decay. However, grab samples may not record variations in released tritium unless the samples are collected frequently. For example, eight-hour, daily, or weekly samples will not record a peak release amount of tritium occurring in the span of perhaps one hour. More frequent grab samples become costly in terms of labor time and analysis cost.

To obtain better monitoring of tritium releases, several methods have been developed to continuously monitor tritium in effluent water. Savannah River National Laboratory (SRNL) has tried two methods. One method employed in the early 1990’s was diverting a small stream of effluent water over a plastic solid scintillant and using photomultiplier tubes to read the light emission from the tritium beta decay in an analysis cell.[6-7] This was the method chosen for continuous monitoring after a 1991 tritium release from the SRNL K reactor primary coolant. The K reactor was a fission reactor cooled by heavy water (D_2O); it rejected reactor heat to the environment. The primary coolant heat exchanger tubes leaked, allowing tritium produced from the D_2O to enter into the secondary coolant water that is discharged to a nearby river. This leakage resulted in a small off-site release event.[6-8] The SRNL prototype tritium monitor was then installed at the beginning of 1992 as a required monitor to alert of any new unrealized tritium releases from the K reactor. This chapter presents an analysis of the operating experiences of continuous tritium-in-water monitors.

6.1 Monitor Operating Experiences

Monitoring effluent water can be a challenge. The effluent water is often dirty and requires filtration. There is always some dirt, silt, slime, and also algae that passes through the filters and can foul the scintillation apparatus. Also, luminescent materials and radioactive species other than tritium can be in the effluent water; these interfere with measurement. Chlorine has a chemiluminescent reaction with tritium that results in false readings with photomultiplier tubes; the chlorine is usually removed with charcoal filters, but charcoal filters can result in breakaway particulate, or fines, in the filtered water. Filter clogging tends to delay instrument response time. Using small pore size filters to prevent fouling leads to high frequency of filter replacements.[6-9] Despite these challenges, solid scintillant monitors were selected for use at SRNL.

Three types of information are needed to calculate the failure rate of an equipment item. The count of failure events, the number of equipment items in operation, and the time span of interest. The count of events came from SRNL documents, including reports filed in the US Department of Energy Occurrence Reporting and Processing System (ORPS).[6-10]

Solid scintillator monitors were installed at SRNL at three locations: the outfall from the K reactor secondary coolant, the sewer effluent line from the heavy-water purification area, and on the discharge from the effluent treatment facility.[6-11] From documentation, one unit was placed on the K reactor outfall, and one unit was used at each of the other two locations. The first solid scintillator unit began operation in January 1992, the others in 1993, and they operated through 1997 according to the ORPS reports. After that time, changes in facilities and other monitoring types negated the need for the solid scintillator monitors.

The solid plastic scintillator monitor used a metering pump with a flow rate of 100 ml/minute to draw samples of effluent water. The sample water was then rough filtered, followed by a polishing filter. A small portion of the water was collected in a 1-liter surge tank. A positive displacement pump moved surge tank water through ion exchange resins and charcoal filters to the plastic bead scintillation analysis cell. Strong acid cation resins were used to reduce precipitates (e.g., iron and other metal hydroxides) that would foul the monitor and the charcoal filter was used to reduce organic contaminants in the water stream. An ultraviolet light was used to sterilize the sample water to reduce algae. A biocide liquid was added to the sample water at the 3 ml/minute positive displacement pump for biological control of algae. The surge tank allowed the monitor to have ~8 hours of hold time to provide for filter changeouts and other maintenance without turning off the monitor. Preventive maintenance time durations were not given for these solid scintillant units, but such maintenance included weekly replacements of polishing filter cartridges and ion exchange resin columns. Analysis cells were not replaced as frequently. Daily surveillances were performed on the units. Early in the operation of these units the staff recognized that the monitors were labor intensive because of the requirement for water cleanliness in the analysis cell. Several improvements were made in the first years of operation to decrease the labor needed for monitor servicing. Reusable resin beds were installed to allow a choice of ion exchange resin media[6-12] to gain longer resin lifetime and decrease the frequency of resin bed changeouts to less than once a week. Figure 6-1 gives a diagram of the monitor. The monitor sensed tritium at 56 Bq/ml (or 1.5 nCi/ml),6-8 and the alarm point was 3 nCi/ml.[6-13] After the 1991 tritium release event, the tritium levels in the effluent water were in the <1 to 500 pCi/ml range, and did not reach the monitor alarm point.[6-13]

One of the SRNL units that monitored effluent water to the process sewer was struck by lightning in July 1995, but it recovered operation.6-14 The staff installed a ground fault protective circuit for the 120 Volt power to the unit. The lightning strike has not been included in the failure rate, since the failure rate is developed from the inherent reliability of the monitor subcomponents rather than external events. However, this event should be noted since this type of monitor may not be housed within a building like many other types of radiation monitors.

These monitors were meant for continuous operation, but rather than assume 8760 hours per year as is standard in failure rate calculations for continuously operated equipment, the failure rates were calculated based on an operating hours estimate of 8700 hours per year. This time accounted for an assumed 60 hours per year (i.e., a little more than one hour per week) of preventive maintenance outages for cleaning, seal replacement, calibration, and other maintenance.

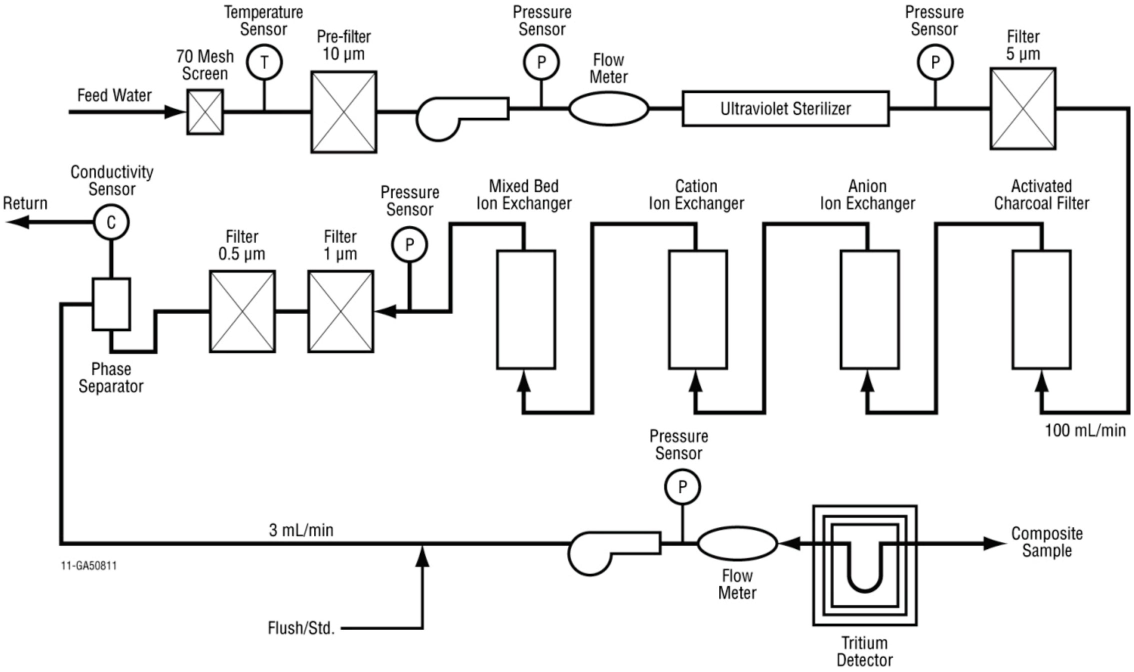

Figure 6-1. Sketch of a tritium in water monitor.

6.2 Reliability Data

The failure rate calculations were based on three effluent monitor units (the prototype for 6 years, and the two other monitors for 5 years), and a total of 17 failures reported in the ORPS. The prototype operated singly in the first year, and examination of the failure reports in Table 6-1 showed that there were many failures in that year, so that year was assumed to be an "early life" time period with the single prototype monitor; early life is typified by a large number of failures. There were twelve failures in the first year and 5 failures in the remaining time of operation with the three monitors that were improved from the lessons with the first operating year of the prototype monitor. Some equipment items exhibit an "early life" period of less than a year, some electronics are less than 6 months early lifetime, and some mechanical items can be more than a year. Therefore, the time duration of one year early life appears to be a reasonable assumption.

This is a small sample of effluent monitors operating over a modest time period, so the error bounds of the failure rate will be given attention. The early life failure rate is λ = failure count/total operating time, or 12 failures/(1 unit•8700 hours/y•1 y), giving 1.4E-03/hour. The 95% upper bound is calculated with a Chi-square distribution, λupper = χ2(0.95,2(n+1))/2T [ref 6-15], where n=failure count of 12 and χ2(0.95,26)=38.885. λupper = 38.885/(2•8700 h) or 2.2E-03/hour. The 5% lower bound λlower = χ2(0.05,2n)/2T [ref 6-15] is 13.848/(2•8700 h) so λlower = 8E-04/hour. The failure rate for the longer, useful life period of time is λ = 5 failures/(3 units•8700 h/y•5 y) or 4E-05/hour. The 95% upper bound failure rate for the useful life period is λupper = χ2(0.95,12)/2(3 units•8700 h/y•5 y) or 21.026/261,000 which gives an upper bound of 8E-05/hour. The 5% lower bound is 1.5E-05/hour. Comparing the average of the early life failure rate of 1.4E-03/h and mature life constant failure rate of 4E-05/h gives a factor of 35 difference in the two values, which is a large difference for early life and mature life failure rates. The prototype operating as one unit for a year is not considered to be a good indicator of the early lifetime of these monitors; in this case the prototype was used to uncover operations problems that were

Table 6-1. Failure Report Data on SRNL Solid Scintillant Monitors Failing to Function

SRNL ORPS Report Number	Affected Component	Description of Monitor Fault
92-0030	Valve	No effluent flow to analysis cell due to a clogged needle valve that throttles water flow to the monitor
92-0047	Pump motor	Thermal overload trip, reset
92-0053	Analysis cell	Blockage of analysis cell in flow-through system caused excess effluent and a pressure build up in surge tank
92-0054	Pump	Main pump inner cavity rubber hose rupture, no flow to analysis cell
92-0058	Filter	Filter housing leakage past filter, fouling in analysis cell
92-0074	Filter	Filter housing seal plate cracked, leaking water, no flow to analysis cell
92-0075	Filter	Debris trapped in filter, inlet filter clogged
92-0076	Flow meter	Clogged flow meter, foreign material intrusion
92-0080	Filter	Worker installed incorrect particle size filter, filter clogged, no flow
92-0095	Pump	Pump casing seal gasket failure, water leak, no flow
92-0132	Pump	Water flow to analysis cell clogged from algae growth in clear tubing
92-0167	Pump	Pump rubber hose rupture, water leak, no flow
93-0112	Pump motor	Starter switch corroded, transformer defective, no water flow
93-0133	Pump	Pump hose rupture, water leak, no flow
93-0139	Valve	Relief valve leaking past seat, water not flowing to analysis cell
94-0007	Pump	Cracked bushing, water not flowing to analysis cell
95-0028	Pump	Worn out, water not flowing to analysis cell

addressed in the design of the next set of monitors to be installed, and the prototype was modified with the improvements as well. The failure rate of 4E-05/h for the mature lifetime with three monitors over 5 years gives a result comparable to other types of monitors from previous chapters: tritium-in-air monitors, 3.5E-06/h, stack monitors, 1E-04/h, continuous air monitors, 2.7E-05/h, and combustible gas monitors, 1E-05/h [ref 6-16].

Given that this water effluent monitor is more complex than the tritium in air monitors that collect and analyze air samples, the difference in their failure rates is expected. However, it must be remembered that this is a small set of effluent monitors and small operating time duration with monitors that are mainly experimental in nature; they are not commercial off-the-shelf units. It is interesting to note that the failure events discussed in Table 6-1 did not mention any problems with the photomultiplier tubes. Presumably the lack of failures of these tubes is because they are highly matured equipment in wide use in the radiation counting industry. The solid scintillant monitors were noted to be complex instruments that required several levels of water filtration and sterilization (biocide addition and ultraviolet light) to combat fouling and algae growth so the instrument could give a true reading. The complexity adversely affects the monitor reliability and also maintainability.

6.3 Maintenance Data

Some maintenance times for the solid scintillant tritium monitors were found in the event reports and other documents; these are summarized in Table 6-2. As noted above, the monitors had a surge tank that collected up to 8 hours of ‘time-history’ water; this provision was made to allow for maintenance time without sacrificing analysis of effluent water that flowed to the river or sewer. It has been seen with maintenance of other radiation instruments that most routine tasks can be completed in less than 8 hours (see chapters 2 through 5). The tritium monitors also had a second water pump installed since the positive displacement pump unit tended to be a problem area for these monitors. For that pump, a rubber hose provided the displacement volume of water; a metal cam turned to flatten the rubber hose to force the flow of a hose volume of sample water. The exterior of the rubber hose was immersed in glycerin inside the pump casing to lubricate the hose and reduce hose wear from the action of the cam. However, the hose would wear nonetheless and in short times it would begin to leak, resulting in monitor failure because the leaking water would bypass the analysis cell.

Table 6-2. Maintenance Information for Tritium Effluent Water Monitors

Corrective Maintenance Task	**Task Time Duration**
Water pump trip, pump was restarted	24 minutes active repair time for a technician to troubleshoot and return unit to service. Total down time 5.3 hours.
Water filter clogged, filter was replaced	22 minutes for a technician to replace filter and return unit to service. Total down time 3.75 hours.
120 Volt transformer and switch for pump motor failed, parts were replaced	Parts replaced. 11 days to return to service.
Positive displacement rubber hose in pump failed, hose was replaced	Parts replaced. 10 hours from failure to returning monitor to service.
Pump failure, cracked bushing leaked water, bushing was replaced	Parts replaced. 7 days to return unit to service.
Preventive Maintenance Task	**Task Frequency**
Monitor check	Brief technician check each 4 – 6 hours
Relief valve check	Technician tests relief valve each 36 months
Positive displacement pump rubber hose replacement before failure	Technician replaces this hose after each 600 hours of operation
Analysis cell source check	Brief technician source check daily

The solid scintillator monitors discussed above required more labor time than other radiation monitors for cleaning and replacing mechanical water filters, ion exchange resins, and charcoal filters that were placed on the water stream to prevent impurity fouling of the plastic scintillant. The ultraviolet light and biocide water treatment to preclude algae growth on the plastic beads also required periodic maintenance. A second monitoring approach was investigated at SRNL to relieve the maintenance burden involved with operating the monitors that used plastic scintillants. The second approach used liquid scintillant in a field LSC. This approach used flash distillation of the sample water for purification, then injected a small (<1 ml) amount of liquid scintillant into a sample water stream and measured the emitted light with photomultiplier tubes. This method was used at SRNL for a few years with success. Originally, the cost of liquid scintillant in quantity (several liters/month per monitor) and scintillant chemical pollution (chemicals such as toluene that give high counting efficiency have low thresholds for environmental releases) in the effluent water were believed to preclude its use. However, the liquid scintillant quantity needed was reduced to ml/hour usage and researchers found that some of the chemical could even be reclaimed for reuse - thus reducing releases to the environment. SRNL began using this approach in the mid 1990's.[6-17] Due to reductions in facilities requiring tritium effluent monitoring at SRNL, there is insufficient data being reported on the liquid scintillation type of monitor to calculate failure rates or discuss maintenance tasks.

6.4 Conclusions

It is important to have early tritium detection in all types of effluent water to provide rapid mitigation procedures. The reliability of tritium-in-water monitors is very dependent on the attention given to preparation of the effluent water. Current operating experiences with monitor maintenance and failures are limited, and this chapter reports on what is available for an early type of effluent water monitor.

Maintenance information demonstrates the active repair time can range from 22 minutes for filter replacement to 11 days downtime while waiting for a part to arrive on site. The SRNL solid scintillant tritium effluent water monitor useful life calculations for this small set of monitors give an average failure rate of 4E-05/hour for failure to function. The issues associated with this failure rate are mostly sample water pump problems.

6.5 References

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7. Survey Meters

An important aspect of radiological safety for personnel is performance of radiological surveillance. The surveillance gives the data needed to evaluate radiological conditions in rooms or areas of a facility and prescribe appropriate engineering and administrative controls to protect the workers. Personnel trained in radiation survey techniques and operation of monitoring instrumentation conduct these surveys. Proper evaluation of radiation levels in areas where work is to be performed ensures that no unanticipated personnel exposures occur and maintain worker exposures to within established guidelines and regulatory limits.[7-1]

The frequency of performing radiation surveys depends on various parameters, with an important parameter being the potential for fluctuation of radiation levels in the given area of the facility due to any changes in facility conditions or operating modes, e.g. shutdown versus operation. Another parameter is how often workers will access the given area. In the US, there is a regulation that continuously habited areas (that is, workers present 2,000 hours per year) of a nuclear facility must maintain exposure levels below an average of 5 μSv/h (0.5 mrem/hour) and as far below this average as reasonably achievable.[7-2] A typical survey meter used for area surveys is shown in Figure 7-1.

Figure 7-1. A portable survey meter with a hand-held probe.

7.1 Survey Meter Data Assessment

Ballinger[7-3] gave some data on hand-held survey instruments used in nuclear fission power plants. These data are repeated in Table 7-1. On average, a fission power plant, or a similar size nuclear facility, would have more than 100 survey meters of various types on site.

Ballinger pointed out that an above-average instrument inventory at a facility and a low number of instruments in active service means that in general, the repair practices at that facility are poor and there is also perhaps no attempt to retire obsolete instruments that tend to require frequent repairs. An in-service instrument percentage of 80% is attainable as seen in Table 7-1 and should be a goal for all facilities.

Bunker[7-4] discussed obsolete portable radiation survey instruments. Obsolescence is defined as excessive cost, downtime, and personnel exposure resulting from frequent instrument repairs. Another obsolescence issue is that personnel lose confidence in the accuracy and reliability of instruments that frequently cease to operate or give erroneous readings. Bunker stated that many power plants do not have a defined instrument retirement criteria, so instruments are only disposed of when they are damaged beyond repair. Another issue for consideration is that as instruments age, when they get very old (e.g., decades old) the manufacturer support fades away from that model and procuring spare parts becomes difficult. Often, an on-site instrument repair shop will begin to cannibalize some units for spare parts to keep others operating. Bunker stated that the typical lifetime for a hand-held survey instrument was 5 to 10 years. The INL experience is that with some new technologies for survey meters an instrument may be replaced in as little as 2 years, but replacement can typically take as long as 10 to 15 years. The Bunker estimate of 5 to 10 years lifetime falls in the middle of the INL experience. It would seem that ten years is a reasonable lifetime estimate for a typical radiation survey meter.

In chapter 2, Table 2-2, a number of generic failure rates were given for radiation monitors or instruments. The definition of these instruments are not specified in most data sources, these could be hand-held Geiger-Müller counters similar to that shown in Figure 7-1 or other types of radiation monitors. Given that the "all modes" failure rates for radiation instruments are on the order of 1E-05/unit-hour, this seems to be a reasonable value to apply to hand-held survey meters. An error factor of ~3 has been assumed on the failure rate given the upper bound failure rates in Table 2-2. No reports or data sets were found in the literature to give a more detailed failure rate estimate for survey meters.

7.2 Calibration and Maintenance Data

Hand-held instrument calibration varies with the type of instrument. Typical calibration intervals seen in practice are 0.5 year, 1 year, and 3 years. The US Nuclear Regulatory Commission (NRC) stipulates in one regulation that instruments used for quantitative radiation measurements, such as dose rate, are periodically calibrated.[7-5] In the well logging section of the Code of Federal Regulations, the regulation states that a beta-gamma radiation survey instrument shall be calibrated at intervals not to exceed 6 months and the instrument shall also be calibrated after servicing.[7-6] The regulation also specifies some aspects of the calibration process: for linear scale instruments, calibrate at two points located approximately 1/3 and 2/3 of full scale on each scale; for logarithmic scale instruments at the midrange of each scale; and for digital instruments, at appropriate points. The accuracy of calibration must be within ± 20% of the calibration standard on each scale. In another regulation, instruments and equipment used for monitoring shall be periodically maintained and calibrated on an established frequency.[7-7] The practice at particle accelerators is that survey meters and detection equipment shall be calibrated at least annually and after each servicing or repair that could affect calibration status. The equipment is also regularly tested for proper operation (once a week for survey meters that are used frequently).[7-8] At the INL, typically the health physics instrumentation laboratory accepts an instrument for calibration and keeps it for 1 week to be calibrated against a known radiation source. Most modern instruments hold their calibration; they tend to not degrade or drift before the next calibration interval. Chida tested twelve Geiger-Müller survey instruments, they gave repeatable results (within 1% variation of the reference measurement) and for units up to ten years of age the units consistently read close to the reference measurement.[7-9] Over ten years of age, the units did not give such accurate results, which supports the ten-year life estimate discussed the previous section. During calibration, a replacement instrument is used in the interim period when the primary instrument is at the instrument shop or calibration laboratory. If there is an urgent need for quick calibration, the instrument can be turned around in one day. Some instrument service companies advertise 48-hour turnaround, and that includes the round-trip shipping time by express package delivery.

Table 7-1. Numbers of Survey Instruments at Selected Nuclear Fission Power Plants[7-3]

Power Plant identifier	Number of β-γ Instruments			Number of Neutron Instruments	Number of instruments in service per plant	Percent of instruments in service per plant
	Low-range	Mid-range	High-range			
1	44	--	28	6	39	50
2	30	40	12	8	32	70
3	30	2	23	1	39	70
4	30	6	50	1	20	70
5	34	340	33	4	164	80
6	--	20	30	1	36	70
7	--	20	83	1	36	70
8	40	120	148	4	117	75
9	14	21	12	3	35	70
10	11	28	15	2	28	50
11	29	23	6	2	15	50
12	30	100	30	3	130	80
13	23	30	15	4	43	60
14	30	77	12	5	74	60
15	--	53	8	2	19	60
16	--	80	25	4	65	60
17	--	30	35	3	17	25
Average	21	58	33	3	53	63

Notes: The beta-gamma instrument low-range is ≤ 2 rem/hour (R/h), mid-range is ≤ 100 R/h, high-range is > 100 R/h. The brand names of the instruments in this survey were well known; these data come from matured components of proven reliability. The authors did not address the on-site repair facilities available to these power plants. The authors noted that use of digital electronics in survey meters has improved their reliability.

Holmes[7-10] discussed that the two Three Mile Island fission power plants, before the 1979 core melt event, had 400 portable radiation instruments between the two reactors. More than half of these instruments were not in calibration at any given time. Calibration practices were not state of the art and were poorly documented. After the 1979 event, a group ten technicians was put in place to handle all of the maintenance and calibration of portable radiation protection instruments. The unit 2 reactor, which had the core melt, had over 1,000 instruments issued in the first 5 years after the event, and this number rose to 1,500 instruments for a few years after that to support the cleanup activities. These instrument inventories are much higher than at a typical fission power plant. Figure 7-2 shows a plot of the number of portable instruments at the site, count of technicians in the instrument shop, and the number of calibrations performed per year over the course of the cleanup activity. It is noted from the figure that the number of instrument calibration technicians was 2 before the core melt accident in 1979, the number of technicians peaked at 12, then over several years declined to 7 persons on staff. Presumably this is due to the more efficient calibration techniques Holmes described since the annual number of calibrations climbed from 300 in 1979 for the 400 instruments at the site to 4,500 calibrations in the 1980's for the ~1,500 instruments at the site. These values suggest an average instrument use period of 4 months between calibrations, rather than the more typical calibration intervals of 6 months, one year, or three years. This increased frequency may have been due to the higher radiation levels experienced during cleanup and the subsequent need for accurate surveys for personnel safety. Assuming the technicians were dedicated to calibrations and no other duties like instrument repair, then a yearly calculation using 1986 data is [(9 technicians)(1800 productive hours/person-year)]/4750 calibrations performed = 3.4 hours per instrument calibration. Calculating the 1981 to 1987 data in this manner and averaging over 7 years gives a value of 5.1 hours per instrument calibration. This time would include the instrument being logged in to the shop, the actual calibration task, documentation of task completion, and returning the instrument to the health physics personnel. Considering the improvements that Holmes[7-10] described, a calibration time of 3.4 hours per instrument is the best estimate.

Battery life is an important aspect of portable, hand-held survey meters. Typically, the manufacturer will make a claim about the expected battery life in a routine application of the instrument. Some instruments use little battery power, some use much power and drain batteries quickly. A typical hand-held beta-gamma meter could have a battery life of 100 to 150 or more operating hours. Given that the meter is turned off during travel time in a facility, and during all other non-use time periods, the 100 operating hours can span a large amount of calendar days (e.g., 30 days or more). 100 hours tends to be a typical battery lifetime for portable survey meters at INL. Battery life is not accounted for in the survey meter failure rate.

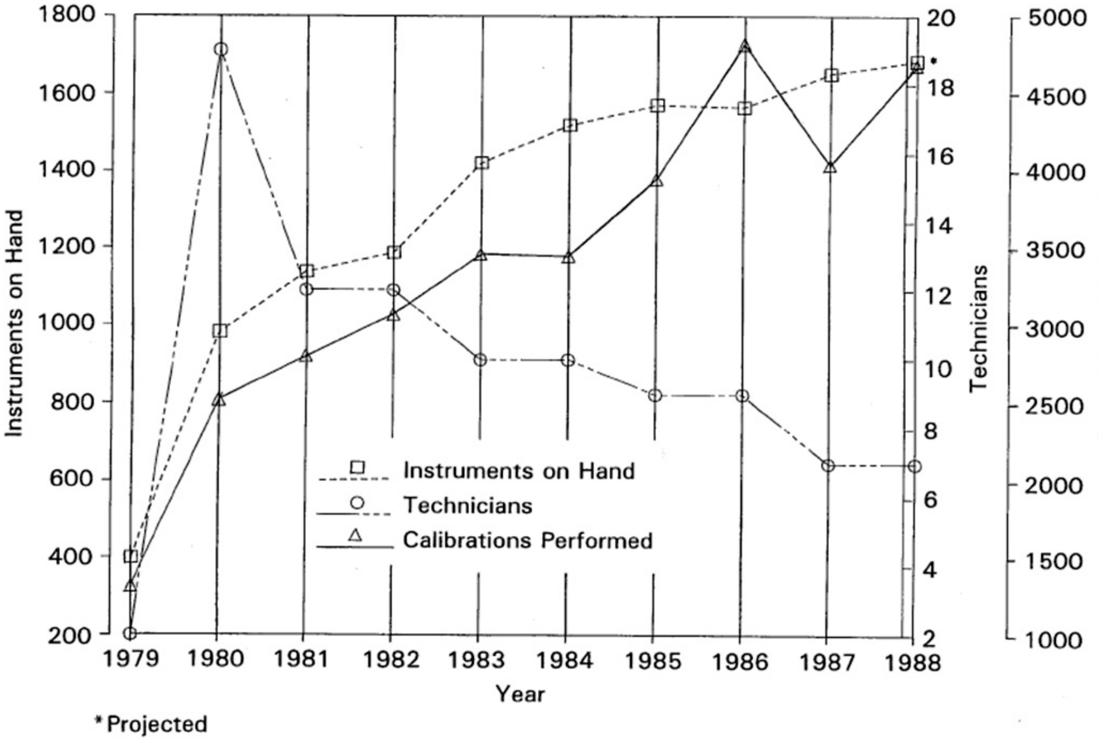

Figure 7-2. Three Mile Island Instrument Shop workload during cleanup activities [7-10].

A literature search was conducted, but no typical times for survey meter repair were found in the literature. Calmus[7-11] gave a time span of 1 to 6 hours to replace a radiation instrument unit, with a most frequent time (the mode of this range) of 2 hours. However, replacing with a spare is not the same as a repair. Tritium monitors, including portable monitors, have a military specification for 0.5 hour mean time to repair.[7-12] However, it is not clear if survey meters can be repaired in a similar amount of time. Hand-held survey meters are now largely using digital electronics that incorporate features of built in testing points and modular components, which suggests the possibility of repairs in a short amount of time. The typical method of repair is electronic module testing and replacement of a module not meeting specifications. Therefore, the unit repair times should not be long, perhaps 0.5 hour to a few hours of active time to test and replace modules and then verify proper operability of the repaired meter. Other repairs, such as to a scintillation probe, are likely to require replacement with a spare probe assembly.

This should be accomplished in short times as well (e.g., a few hours), unless a spare probe assembly is not stocked on site. It is noted that an instrument could be idle, out of service, while waiting for repair, so the total downtime could be a week or more while the instrument waits in a queue for servicing. As pointed out earlier in this chapter, repairs of this magnitude would necessitate a recalibration of the survey meter.

7.3 Conclusions

Without any data sets available, an assumption has been made that the failure rate for hand-held survey meters is on the order of 1E-05/unit-hour, with an assumed error factor of 3. The active repair time is likely on the order of 0.5 hour to a few hours. The downtime could be much longer, perhaps a week or more, depending on the backlog in the instrument shop. Instrument calibration was calculated to be 3.4 hours from one dataset; however, at INL it was noted that the instrument is taken to the calibration laboratory and the laboratory keeps the instrument for a week to perform the calibration.

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