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Operating Experience Review of Tritium-in-Water Monitors

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Susan A. Bruyere
Lee C. Cadwallader

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Susan A. Bruyere and Lee C. Cadwallader

Idaho National Laboratory, Idaho Falls, Idaho

Monitoring tritium facility and fusion experiment effluent streams is an environmental safety requirement. This paper presents data on the operating experience of a solid scintillant monitor for tritium in effluent water. Operating experiences were used to calculate an average monitor failure rate of 4E-05/hour for failure to function. Maintenance experiences were examined to find the active repair time for this type of monitor, which varied from 22 minutes for filter replacement to 11 days of downtime while waiting for spare parts to arrive on site. These data support planning for monitor use; the number of monitors needed, allocating technician time for maintenance, inventories of spare parts, and other issues.

Keywords: tritium monitoring, scintillation counting, reliability, maintainability

1. Introduction

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 picoCuries/liter of drinking water, which is stated to give a dose of 0.04 mSv/year to an individual drinking such water [1]. The US Nuclear Regulatory Commission has a goal value of 0.03 mSv/year for the dose from fission power plant liquid effluents [2] and a tritium average monthly release into sewerage of 0.01 microCurie/ml [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 [4]. More recently, tritium releases from US fission power plants have been a concern for environmental stewardship [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]. 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 in short time intervals. 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 [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 deuterium oxide; it rejected heat to the environment. The primary coolant heat exchanger tubes leaked, allowing tritium to enter into the secondary coolant water that is discharged to a nearby river. This leakage resulted in a small off-site release event [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 paper presents an analysis of the operating experiences of continuous tritium-in-water monitors.

2. 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 radioactives 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

author's email: Lee.Cadwallader@inl.gov

fouling leads to high frequency of filter replacements [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) [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 [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 [12] to gain longer resin lifetime and decrease the frequency of resin bed changeouts to less than once a week. Figure 1 gives a diagram of the monitor. The monitor sensed tritium at 56 Bq/ml (or 1514 pCi/ml) [8], and the alarm point was 3000 pCi/ml [13]. After the 1991 tritium release event, the tritium levels in the effluent water were in the <1 to 500 mCi/ml range, and did not reach the monitor alarm point [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 [14]. The staff installed

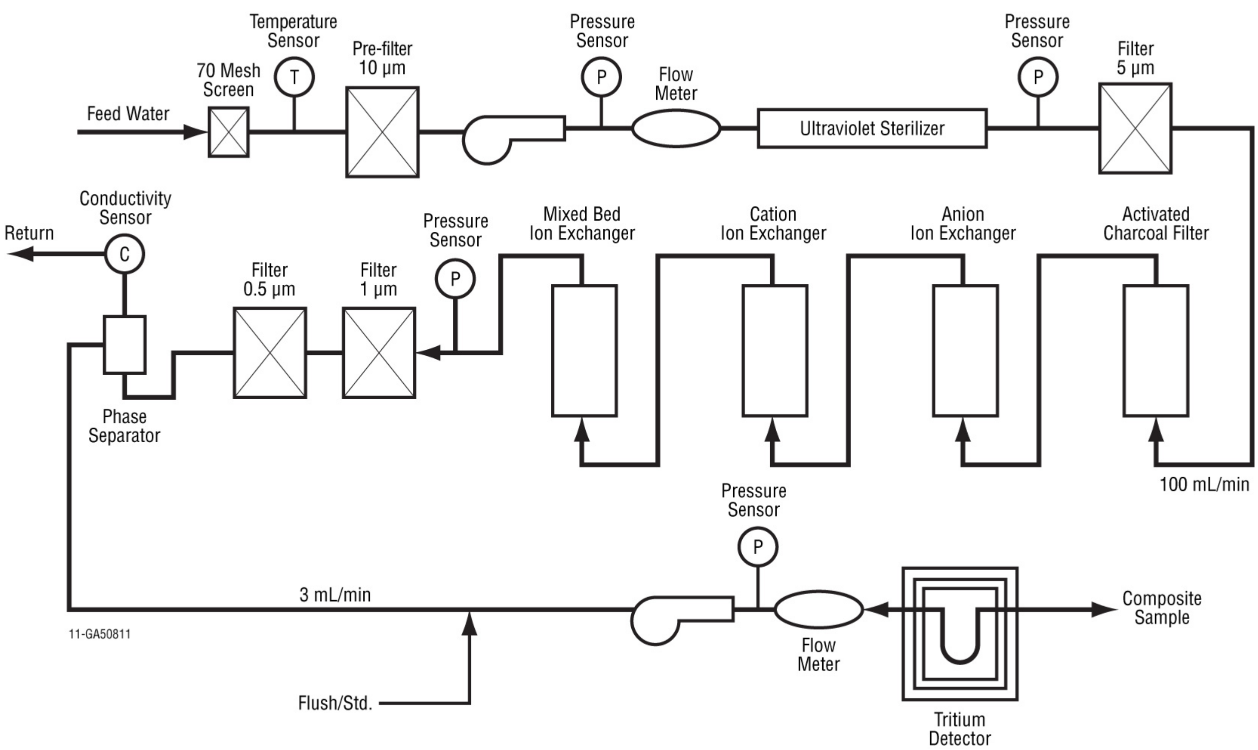

Figure 1. Sketch of a Tritium in Water Monitor.

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.

3. Reliability Calculations

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 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 early life 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, $\lambda_{upper} = \chi^2(0.95,2(n+1))/2T$ [15], where n=failure count of 12 and $\chi^2(0.95,26)=38.885$. λ_{upper} = 38.885/(2•8700 h) or 2.2E-03/hour. The 5% lower bound $\lambda_{lower} = \chi^2(0.05,2n)/2T$ [15] is 13.848/(2•8700 h) so λ_{lower} = 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 $\lambda_{upper} = \chi^2(0.95,12)/2(3$ 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

Table 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

prototype was used to uncover operations problems that were 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: tritium-in-air monitors, 3.5E-06/h [16], stack monitors, 1E-04/h [17], continuous air monitors, 2.7E-05/h [18], and combustible gas monitors, 1E-05/h [19]. 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 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 suggests adverse issues with monitor reliability and also maintainability.

4. 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 2. As noted above, the monitors had a surge tank that held 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 many of the more routine tasks can be completed in less than 8 hours [16-18]. 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.

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 sensed 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 [20]. 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.

Table 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

5. Other Types of Monitors

Other monitoring approaches also exist, such as a large surface area detector [7] or flashing a small sample of water to steam in a chamber and reading the beta particle emissions, then condensing the steam back to water for readmission into the body of water. This flashing method appears to hold promise; it has been investigated at the US Nevada Test Site for sampling very low levels of tritium in the water retrieved from boreholes [21]. Of course, this water flashing method would have to be adapted for effluent stream usage. Presently, there is little field experience data on instruments using this approach, so it cannot be investigated here.

While the solid and liquid scintillator methods may not be the best solution for continuous monitoring of effluent water from fusion plants, these operating experience data do give a failure rate and some maintenance values from one generation of complex solid scintillant monitors. Given the premise that simpler components tend to have higher reliability than complex components, the values found here could be thought of as a guide or an upper bound reliability for simpler effluent monitors to be used in the future.

6. 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 paper reports on what is available. 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.

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