LA-UR-83-2036

CONF-830709--28

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LA-UR--83-2036

DE83 015259

TITLE: SMARTER RADIATION MONITORS FOR SAFEGUARDS AND SECURITY

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SUBMITTED TO: INMM 24th Annual Meeting
Vail, Colorado
July 10-13, 1983

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SMARTER RADIATION MONITORS FOR SAFEGUARDS AND SECURITY*

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ABSTRACT

Radiation monitors for nuclear safeguards and security depend on internal control circuits to determine when diversion of special nuclear materials is taking place. Early monitors depended on analog circuits for this purpose; subsequently, digital logic controllers made better monitoring methods possible. Now, versatile microprocessor systems permit new, more efficient, and more useful monitoring methods. One such method is simple stepwise monitoring, which has variable alarm levels to expedite monitoring where extended monitoring periods are required. Another method, sequential probability ratio logic, tests data as it accumulates against two hypotheses—background, or background plus a transient diversion signal—and terminates monitoring as soon as a decision can be made that meets false-alarm and detection confidence requirements. A third method, quantitative monitoring for personnel, calculates count ratios of high- to low-energy gamma-ray regions to predict whether the material detected is a small quantity of bare material or a larger quantity of shielded material. In addition, microprocessor system subprograms can assist in detector calibration and trouble-shooting. Examples of subprograms are a variance analysis technique to set bias levels in plastic scintillators and a state-of-health routine for detecting malfunctions in digital circuit components.

INTRODUCTION

Radiation monitors for nuclear safeguards and security search personnel, packages, and motor vehicles for gamma radiation that is spontaneously emitted by diverted or misplaced nuclear materials. The instruments range from small hand-held monitors to large vehicle monitors, but they all have a common element: an electronic circuit that detects a transient diversion signal embedded in a steady background signal. Transient detection circuits have evolved from simple analog methods to today's more complex digital control circuits that not only detect transients but also can carry out more complex tasks to improve monitoring performance or aid in calibration and trouble-shooting. Two examples of well-established digital methods are a sliding interval scaler[1] that matches a count interval to a transient-signal time profile and an S-fold scaler that measures the time interval between groups of S detected events to rapidly detect transients in low-intensity neutron signals.[2] More recently, microprocessor decision logic based on sequential probability ratio testing has shortened waiting times in monitors that require fixed count intervals. In a quantitative radiation monitor for nuclear safeguards,[3] sequential testing reduced the average waiting time from 3 to 0.7 s. Two examples of state-of-health functions that can be carried out by microprocessor controllers are statistical verification of input data[4,5] and circuit-component self tests.

The basic tasks of monitor control circuits include radiation measurements to determine decision logic parameters or to detect transient signals; other tasks identify background periods, monitoring periods, and proper or improper monitor operation. A list of individual tasks follows.

- Determine the state of health of the electronic circuit components.
- Perform statistical analysis of radiation detector data.
- Determine whether the monitor is occupied or not.
- Determine a background radiation level and whether it is within operational limits.
- Calculate the monitoring decision levels.
- Measure a monitoring radiation level and test it.

Before reviewing control logic methods, it seems best to give an elementary example of the way that radiation monitors detect transient diversion signals. A gamma-radiation detection system that monitors a region of space and produces a signal in proportion to the detected radiation intensity senses diversion in that region by comparing the normal gamma-ray background intensity to the intensity during the monitoring period. The comparison will not require an exact correspondence between the two intensities because there

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*This work was performed under the auspices of the US Department of Energy, Office of Safeguards and Security.

will be statistical error in both intensity measurements (however, we usually try to make the statistical error in background negligible). Thus, a typical method—digital, for example—compares the monitoring count to the background count plus an increment. The increment is important because it establishes both the detection sensitivity and the false-alarm rate. Choosing B to represent the expected background count during a monitoring interval and A to represent the alarm level, three examples of alarm levels are

$$A = B + K ,$$

$$A = B + F \cdot B ,$$

$$A = B + N(B)^{0.5} .$$

The first alarm-level example, from a personnel monitor at the Oak Ridge/Y-12 Plant, simply adds a fixed increment to the background. The second example is found in some hand-held monitors. The factor F is a fraction, typically 0.30 or 0.40. In the third example, also for a personnel monitor, the increment is an integral multiple, N of the standard deviation, σ, of the expected background count, the square root of B. These examples all operate in the same way: a monitoring count is compared to the value A and if the monitoring count exceeds A an alarm sounds.

Each method of calculating an alarm level can be made to have the same false-alarm rate and detection sensitivity as the other methods at one background intensity. Then a monitor using any one of the alarm-level examples will perform the same as it would with any other example. However, as the background intensity changes, the behavior of a monitor will differ with each alarm example. The first example has constant detection sensitivity because K is fixed; however, the false-alarm rate increases with background intensity. The second example will decrease both its detection sensitivity and its false-alarm rate at higher backgrounds. The reason is that the increment F • B becomes a larger quantity, thus decreasing sensitivity, as B increases. Correspondingly, the false-alarm rate decreases because F • B is larger relative to the standard deviation. On the other hand, in the third example, the false-alarm rate remains unchanged and the sensitivity decreases, but not as much, as background increases.

CONTROL CIRCUITS FROM THE PAST DECADE

An Analog Method

A dependable method of carrying out monitoring decision procedures is an analog method that compares monitoring intensities to background intensities by means of the response of two circuits with different time constants (Fig. 1). The slow circuit remembers background intensities over a period of perhaps 20 s whereas the faster monitoring circuit has a short, 0.4-s or so, time constant. The monitoring decision is made by a simple comparitor that has a fixed offset built into it. The fixed offset cannot be adjusted, hence calibration of the monitor involves scaling the input an analog signal from a ratemeter with a voltage divider until the proper sensitivity and false alarm rate are achieved.

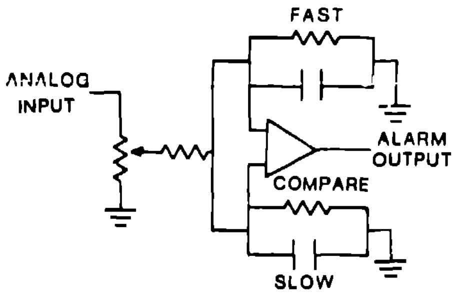

Fig. 1.
This analog transient-detection method makes use of the different time response in parallel circuits. In personnel doorway monitors the time constants are about 20 s for the background circuit and 0.4 s for the monitoring circuit.

Such a manual adjustment procedure is a drawback to analog monitoring circuits. Because three separate comparison circuits are needed for monitoring and background limit tests, three separate series of observation and adjustment are necessary. Major changes in background make it necessary to change rate meter scales and repeat the entire series of adjustments. Minor changes in background can influence the detection sensitivity and false-alarm rate; these parameters increase or decrease with the corresponding background change unless the monitoring potentiometer is readjusted. Both background and monitoring circuits operate continuously. Continuous operation and a properly chosen time constant for the monitoring circuit ensures that the monitor will detect an optimum portion of a transient signal. Although an occupancy monitor is not necessary for this detection circuit, it does inhibit announcing false alarms that take place when the monitor is unoccupied. The analog method is still available in some National Nuclear Corp.[*] doorway monitors and is more fully described in Ref. 6.

Sliding-Interval Scaler

The sliding-interval scaler is a digital technique that, as with all digital techniques, has two immediate advantages. One is that no sensitivity or false-alarm calibration procedure is needed. The other is that background and monitoring intensities can be measured by one set of hardware; an occupancy sensor determines which measurement is under way. The advantage that accrues from the occupancy sensor is that neither source passage nor queueing in the monitor will contaminate a background measurement, which takes place only when the monitor is unoccupied.

In contrast to the single-interval test described in the introduction, the digital sliding-interval technique divides a counting-time interval into subintervals and

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[*] National Nuclear Corp., Mountain View, California.

compares the monitoring count to the alarm level each time a new subinterval is accumulated. For instance, dividing a 1-s count interval into four subintervals (Fig. 2) leads to comparing the sum of four subintervals four times each second. As each new 0.25-s subinterval is accumulated, the oldest one is discarded. This method requires a slightly larger alarm increment to reduce the false-alarm probability because four times as many comparisons are made. However, when the technique can closely bracket a time-varying transient signal—for example, in a walkthrough personnel monitor—the increase in detected signal more than offsets the increase in the alarm increment. The sliding-interval technique for radiation monitors was devised by C. N. Henry of Los Alamos and is similar to the moving-average method of stock market analysis. The technique has been used in a personnel portal monitor,[1] a vehicle portal monitor,[7] and in a hand-held monitor available from TSA Systems, Inc.*

S-Fold Logic

Another technique devised by C. N. Henry implements a suggestion of R. D. Evans for detecting transients in very low-intensity counters such as neutron detectors. The technique is called the S-fold method, after the analysis of pulse counting with a prescale factor S by Evans.[9] The circuit[2] (Fig. 3) uses background events prescaled by S for long-term adjustment of a clock pulse rate. In the short term, prescaled input events also reset a scaler that counts the clock pulses. Thus, the system has a background-adjusted timer to measure the elapsed time between S events. By measuring a constant average number of scaler counts at all backgrounds, a single alarm level can be used. The alarm level is determined from Poisson statistics to give the required false-alarm rate and, in this instance, an alarm occurs when the monitoring count is less than the alarm level. The strong point of this method is that it has no fixed or subdivided time interval. The decision frequency is determined by the frequency of incoming events; thus, a transient is tracked and detected whenever it appears as was the case in the analog method. On the other hand, fixed-interval counting requires long counting intervals at low count rates so that when a transient appears, there may be a considerable delay before the interval is completed and an alarm sounds.

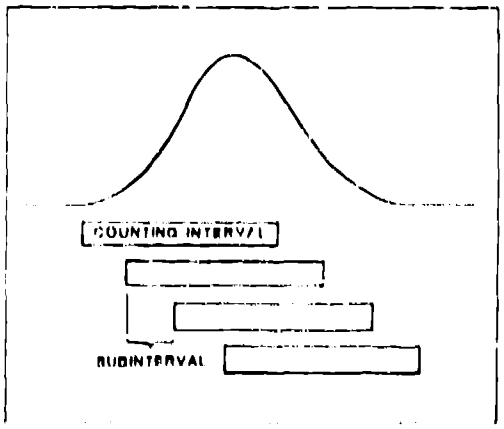

Fig. 2.
The sliding interval technique subdivides counting intervals so that a sliding subinterval sum will eventually bracket transient diversion signals.

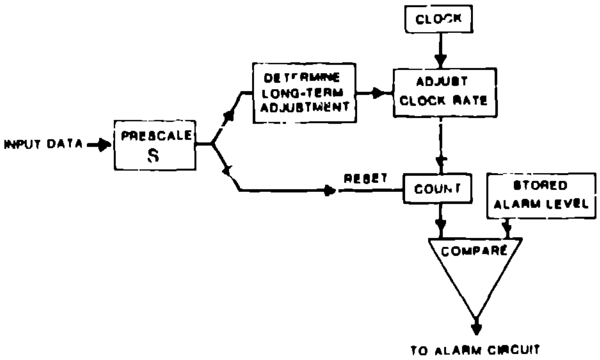

Fig. 3.
The S-fold technique measures the time interval between groups of S counts. A background adjustment to the clock rate makes it possible to use the same alarm level for all background intensities.

NEW TECHNIQUES FOR MICROPROCESSOR SYSTEMS

Stepwise Monitoring

The stepwise method is an elementary means to shorten the monitoring time in monitors that require a person or vehicle to remain stationary during a monitoring period. The monitoring time interval is divided into a few subintervals, which are accumulated and tested until a decision is reached. The difference between this and the sliding-interval technique is that three different counting times with different alarm levels are involved (Fig. 4). We applied this method to vehicle monitoring in a roadbed monitor that formerly required a 50-s monitoring period. The stepwise controller used 20-s-long subintervals and had a three-step monitoring procedure.

1. Test the first 20-s count against a 2σ alarm level. Terminate monitoring or, in case of an alarm, go on to step 2.

2. Test the sum of the first two 20-s counts against a 3σ alarm level. Terminate monitoring or, in case of an alarm, go to step 3.

3. Test the sum of all three 20-s counts against a 4σ alarm level, which is the original 50-s single-interval decision point. Terminate monitoring or announce an alarm, as appropriate.

It is important to realize that at each step of the stepwise procedure, the tests have the same probability of detecting a diversion signal (in this particular monitor), but they have vastly different false-alarm rates. The first step false alarm probability is 2.3%, which would be unacceptable in a single test procedure. However, in this case that alarm level allows

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*TSA Systems, Inc., Boulder, Colorado.

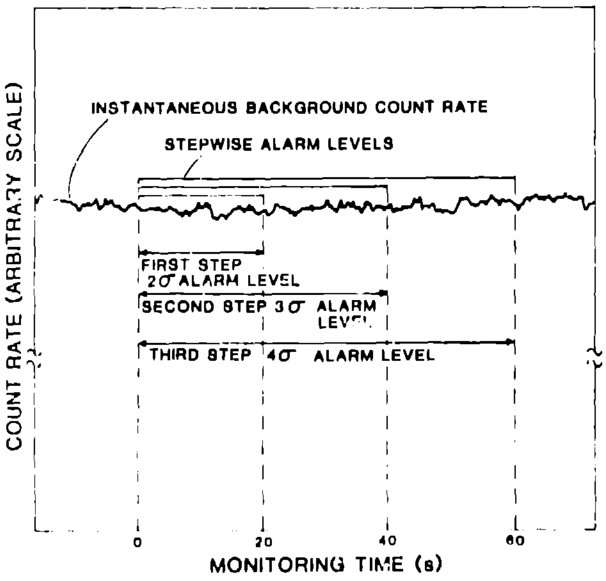

Fig. 4.
Stepwise monitoring permits most decisions to be made during the first, 2σ interval. For the 2.3% or so occasions that a false alarm occurs in the first interval, testing continues through 3σ and, if necessary, 4σ intervals until a final decision can be made.

all but 2.3% of the normal traffic to depart while detaining only a few vehicles for additional counting intervals. Thus, the monitoring delay is much less noticeable compared to waiting 60 s for a decision. The few vehicles that experience false alarms and longer monitoring times are detained about as long as all traffic had previously been detained. This method was evaluated in a roadbed monitor[8] for a short period of time, but is currently being replaced by the next technique, sequential testing, which also can make quicker decisions. The sequential technique supplants the stepwise technique because its detection and false-alarm performance are easier to predict and do not vary as much from one type of monitor to another.

Sequential Probability Ratio Testing

This sequential method for radiation monitors derives from the work of A. Wald[10] to reduce the number of observations required to achieve a specified degree of quality control in manufacturing. Wald applied the sequential probability ratio test to normally distributed quality control measurements, but it applies as well to nuclear counting statistics whether they be Poisson or normally distributed. Analysis of the technique for the normally distributed nuclear counting application is particularly simple because the standard deviation can be estimated as the square root of B.[11]

A sequential probability ratio test is a form of hypothesis test in which the question to be decided is whether the counts observed in one or more short sequential count intervals are from a distribution of background having mean B0 or from a distribution of background plus a transient signal with mean B1. Each step in a sequence is tested against two decision thresholds, one for background and one for background plus transient, until a decision—background or background plus transient—can be made. When no decision can be made, another measurement step is carried out and tested—up to a maximum number of steps in practical situations.

The quantity tested is, for example, the ratio of the normally distributed probability that the observations are from a background-plus-transient distribution to the probability that the observations are from a background distribution. After n observations have been made, the sequential probability ratio is simply the product of the probability ratios for each step,

$$SPR_n = (PR_1) \cdot (PR_2) \cdot \ldots (PR_n) \quad ,$$

where each probability ratio in the expression has the form

$$PR_i = \frac{\exp\left[-0.5 \cdot (x_i - B1)^2/\sigma^2\right]}{\exp\left[-0.5 \cdot (x_i - B0)^2/\sigma^2\right]} \quad .$$

The subscript i denotes a particular step number in a sequence, x_i is the observed count at that step, B1 is the mean of the background plus transient (to be determined in a moment), B0 the mean of background alone, and σ the common standard deviation of the two distributions, $(B0)^{0.5}$. At each step, n, of the sequence two tests are made. First, test for $SPR_n > TA$, which indicates that the counts are from background plus signal; second, test for $SPR_n < TB$, which indicates that the counts are from background alone. The quantities TA and TB are numerical decision thresholds (defined below). If neither case is true, the sequence continues with one more observation. In practice, the test sequence must terminate and the test values are chosen to make that happen under most circumstances. In case the sequence does not terminate after a maximum number of steps, a separate arbitrary or rational procedure can terminate the sequence.

Another practical matter is that the logarithm of the probability ratio, z_i, is more easily calculated than the ratio itself. Successive values of the logarithm

$$z_i = \left[0.5(x_i - B0)^2/\sigma^2\right] - \left[0.5(x_i - B1)^2/\sigma^2\right]$$

are summed instead of multiplying the probability ratios themselves. The sum z_n, which may be further simplified for calculation, is tested against the logarithm of the decision thresholds TB and TA. Wald gives us estimates of the threshold values in terms of the desired false-alarm probability FAP and detection probability PDET as follows,

$$\log(TA) = \log(PDET/FAP) \text{ and}$$

$$\log(TB) = \log[(1-PDET)/(1-FAP)] \quad .$$

These test threshold estimates may, in some cases, require slight changes to achieve the required false-alarm probability.[11]

The final parameter value, B1, must be carefully chosen to ensure that a decision can be reached in the time available for monitoring. Our first experience with sequential testing was a safeguards application in an enrichment plant,[12] for which we derived B1 from Wald's analysis of the probability of termination on or before a given number of steps. Later, as we evaluated sequential testing for personnel monitors, it became apparent that B1 could be derived by analogy to the alarm level determined in the sliding-interval method. In fact, with our accustomed value of 0.5 for detection probability and 4 for the sliding-interval sigma multiplier, the complicated expression we had earlier derived is equivalent to the analogous method.

Calculation of B1 begins with estimating the appropriate counting-interval length and maximum number of subintervals for a sliding-interval technique. We use the subinterval length for the sequential count interval. We then express the sliding-interval increment as a fraction of background, B, and multiply that fraction by B0 to obtain the sequential increment. That is,

$$B1 = B0 + \left[4(B)^{0.5}/B\right] \cdot B0 \quad .$$

Our first application of the sequential technique[12] demonstrated that, as Wald had learned, the technique can make more rapid decisions than customary methods. In our case, we made use of the time saving to achieve 95% probability of detection whereas previously, with a single-interval technique, we obtained a 50% value. A second application of the technique was to personnel monitoring in a booth that normally requires a monitoring time of a few seconds. In that case, we made a thorough investigation of the time behavior. We found that, on the average, a background decision took 22% of the customary time when background was really present. False alarms appeared at approximately the predicted frequency.[11] When we introduced transient signals near the threshold of detection, the average number of steps approached the maximum number allowed by the customary method. At higher transient intensity, a rapid decision was again possible. The curve of average sample numbers (Fig. 5) reflects the amount of counting required over a broad range of monitoring intensity.

Besides shortening fixed-counting intervals, the sequential technique can quickly determine background and, thus, be in a position to start a monitoring sequence when a transient appears. For example, in a vehicle portal, radiation from a source can be optimally processed without instrumentation to precisely start the counting sequence. Thus, knowledge of the location and speed of the vehicle becomes less important. The monitor can operate under variable circumstances: for example, if someone drives through the monitor more quickly than expected, the monitor still performs well. An important corollary to this capability is that short-duration noise that might be averaged out in another monitor likely will be detected in this monitor because of the sequential technique. Hence, noise-free operation of the monitor's electronics is very important for sequential testing.

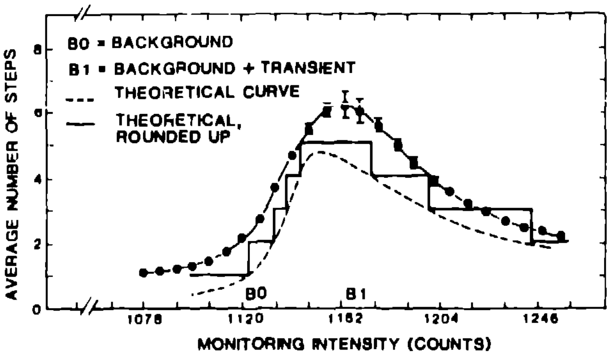

Fig. 5.
The average number of samples that the sequential probability ratio technique uses to make a decision is determined and plotted for various radiation intensities, both below and above the background intensity B0. The plotted values are averages over a large number of decisions. Individual measurements show variation in the required number of steps, which occasionally reach the maximum number of steps allowed near B1. Well away from the value B1 the technique makes its decision rapidly.

Quantitative Monitoring

This technique was evaluated with sequential tests, but in principle the technique can be used with any monitoring method. The idea is to detect diversion and then determine whether the alarm was produced by a small quantity of bare material or a larger quantity of shielded material. The question is an important one in international safeguards monitors that are unattended and lack first-hand investigation of alarms. The means to make a shielding determination is another of C. N. Henry's innovations, a spectrum ratio technique. Monitoring can be carried out in any fashion, but two separate regions of the gamma-ray spectrum are counted and saved whenever an alarm occurs. For example, counts in the normal window and a separate high-energy region can be compared to determine a quality factor that is related to the amount of shielding around the detected material.

An example of the quantitative technique[3] (Fig. 6) illustrates that the amount of shielding can be estimated over a range of shielding thickness. When the spatial response of a monitor is quite uniform and the material present in the monitored area is a specific type, a useful estimate of the diverted mass can be made. Otherwise, the technique simply determines whether or not the source was shielded, which in itself is valuable information. For international monitoring, extremely small quantities of bare material may be difficult to identify in an inventory, hence the quantitative technique can determine when an inventory is worthwhile.

Calibration and Trouble-Shooting Aids

Various calibration techniques are used for radiation detectors. For plastic scintillators[13] a low discriminator setting is essential for best detection efficiency, but the setting must not be low enough to

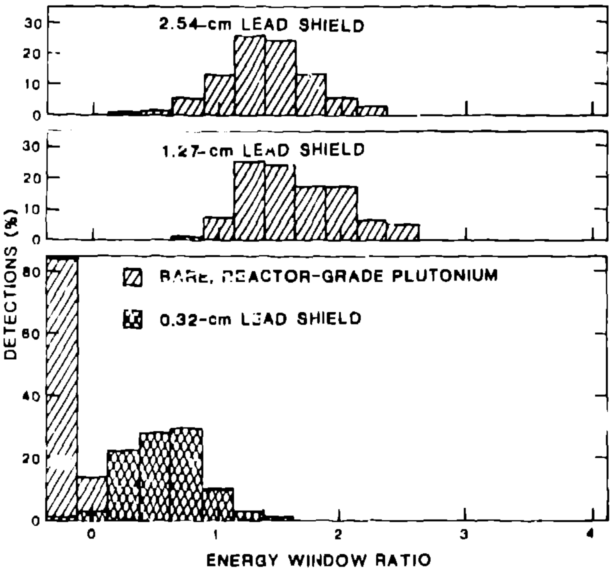

Fig. 8.

Shielded reactor-grade plutonium has an extremely low spectrum ratio when it is bare. Shielding increases the ratio to a limit imposed by scattered radiation from the shield. The dispersion of values from limited counting statistics is narrow enough to coarsely identify the amount of shielding when the type of shielded material is known.

introduce noise. A variance analyzer[4] calculates the mean and variance of a number of counting samples and compares them. These quantities should be almost identical for nuclear counting. By means of repeated variance analyzer measurements, the discriminator level can be lowered to the lowest possible level. Except for very cold detectors, this technique sets the discriminator at the same point that other methods would place it, but it does so in a relatively short period of time.

Variance analysis is also useful in identifying circuit problems that introduce noise. Another valuable trouble-shooting aid is a state-of-health subroutine that executes each time a monitor powers up. The subroutine checks appropriate circuit elements to identify and flag problems before the monitoring program takes control. A typical state-of-health procedure checks the stored programs by tallying a checksum that it then compares to previous values to identify read-only-memory failure. The procedure checks random-access memory by writing a message and then reading it back to detect errors. It checks the timer, used for detector counting, against the microprocessor system clock to ensure that both agree. A final check looks for an incoming detector signal. Lack of signal is the most common failure mode during monitor installation; the procedure immediately flags wiring or other hardware problems that prevent the detector signal from reaching the controller.

The valuable assistance of variance analysis and power-up state-of-health monitoring makes these techniques an indispensable part of all our recently developed monitors.

SUMMARY

The capabilities of control electronics for radiation monitors have greatly expanded in the past few years, both in the enhanced performance of the electronics themselves and in new techniques that refine basic techniques of the past. The sequential and quantitative techniques offer particularly useful advantages without troublesome disadvantages. Rapid decision-making and the ability to track signals, provided by the sequential technique, and the ability to identify shielding, provided by the quantitative technique, are long sought-after goals in radiation monitoring. It is characteristic of the new microprocessor techniques that not only can such methods be implemented but that they can be implemented in a single monitoring circuit.

ACKNOWLEDGMENT

The authors express their appreciation to the many colleagues who assisted in the development of these monitoring methods with their ideas, handiwork, and participation in the evaluation and interpretation of monitoring performance.

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