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APPLICATION OF WALD'S SEQUENTIAL PROBABILITY RATIO TEST TO NUCLEAR MATERIALS CONTROL*

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ABSTRACT

We have replaced traditional analysis methods for nuclear material control monitoring with hypothesis testing, specifically with Wald's sequential-probability-ratio test. Our evaluation of Wald's method, applied in both vehicle and pedestrian SNM monitors, is by Monte Carlo calculation to determine the alarm probability and average monitoring times of the monitors. The vehicle monitor with Wald's test has a much shorter monitoring delay than with traditional methods, without serious compensating changes in operating characteristics. The pedestrian monitor with Wald's method also has advantages over traditional single-interval tests, in that the Wald method duplicates the advantages of a moving-average technique. We verified the Monte Carlo calculations for the pedestrian monitor by means of a special program for the monitor's microprocessor controller. The observations of false-alarm probability and average monitoring time for over 500 000 tests verified the Monte Carlo results.

INTRODUCTION

Nuclear materials management requires analysis of data from measurement systems to determine whether the measurements are consistent with an allowed condition or whether they deviate sufficiently from the allowed condition to suggest diversion of nuclear material. Traditional diversion detection methods that are based on differences between measured and predicted values may be untimely because a long measurement time is needed to achieve adequately low false-alarm probability. Or, on the other hand, traditional methods may seek to be timely by making decisions so quickly that a false alarm becomes highly probable.

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In place of traditional methods, sequential hypothesis tests applied repetitively at the end of each of a number of analysis periods have been described for nuclear material accountancy[1] and for extended containment and surveillance in international nuclear materials safeguards where continuing diversion of very small quantities of special nuclear material must be detected.[2,3] The sequential method mitigates the problems with traditional methods by allowing the measurements to continue when the accumulated data do not warrant a decision. Hence, extended periods of data accumulation can take place whenever necessary, but rapid response is often still possible.

Nuclear material control at material access area boundaries also may benefit from sequential hypothesis testing even though, unlike the preceding examples, monitoring takes place during a relatively short period of time and a decision must be reached by the end of a prescribed monitoring period. For example, we have applied a truncated sequential hypothesis test to vehicle monitoring, where it minimizes the monitoring delay, and to monitoring pedestrians in motion, where the method responds well to diversion signals that have a time profile.

NUCLEAR MATERIAL CONTROL MONITORING

A radiation monitor for nuclear material control measures the radiation intensity in the vicinity of a pedestrian or motor vehicle to search for special nuclear material before granting exit clearance from a material access area. Analysis of the radiation monitoring measurement, basically a comparison of the measurement to its expected result, is influenced by three major factors. First, the expected result must be derived from a prior background measurement alone, rather than from before and after measurements, because the pedestrian or motor vehicle departs immediately on obtaining exit clearance. Hence systematic error may arise in the analysis from detector response variation or from actual changes in ambient radiation intensity with time. To reduce the systematic error, the background must be derived from the most recent, short-term background history of the monitor. The second factor, particularly important for the vehicle monitor where a minute-long monitoring time may be necessary, is that the background counting period that determines the alarm threshold is not much longer than the monitoring period. Hence, statistical error is comparable in both monitoring data and alarm threshold and both errors influence the false-alarm and detection probabilities of the monitor.[4]

A final factor that influences radiation monitor analysis is a decrease in the perceived radiation intensity when the monitor is occupied.[4] Both pedestrians and vehicles can reduce the background radiation field incident on a monitor's detectors by shielding them from the radiation. This effect decreases a monitor's occupied false-alarm probability because the measured intensity in an occupied monitor is less than it otherwise would be. Similarly, the monitor's sensitivity when it is occupied is less because a larger diversion signal is needed for an alarm in the empty monitor. The reduced detection probability could be mitigated by lowering the alarm threshold by an amount equal to the intensity reduction. However, the amount of the intensity reduction varies with the occupant and although some degree of compensation may be possible, the reduction cannot be totally compensated by any simple scheme.

These factors must be taken into account in designing a material control monitor, but there are other considerations as well. Perhaps the most important consideration is that material control has the goal of preventing the diversion of a quantity of nuclear material instead of the more objective statistical goal of detecting variations of more than a certain magnitude from the mean value of the monitor's background observations. In practice, we must rely on the statistical point of view to design and quantitatively predict the performance of a monitoring system, but then we have a great deal of leeway in relating the performance of the monitoring system back to the material control goals. The reason for the latitude is that diversion signal intensities depend on the isotopic content, the physical form, and the position of the diverted material in the monitor.[4]

Rather than pursue material detection goals in this paper, we will simply describe the monitoring system on a statistical basis. The first step in this regard is to point out that we ensure a sound statistical basis for our analysis by testing the statistical performance of each monitoring system as part of its calibration. Our goal is to verify that the observed counting samples follow a Poisson distribution; our monitor calibration procedures include adjusting the discriminator to exclude noise until the measured variance is nearly identical to the measured mean value of the count distribution, as it should be for a Poisson distributed count distribution. This step helps avoid the situation described in Ref. 5 where an extremely broad normal distribution instead of a narrow one equivalent to the expected Poisson counting distribution was observed in a portal monitor.

Keeping the foregoing considerations in mind, we will describe a traditional monitoring system for material control monitoring. Later in this paper, this monitoring system will provide a basis for selecting the parameters for sequential hypothesis tests. The traditional monitoring system has a single-interval test (SIT) characterized by its background determination period, alarm threshold, and monitoring period, which together determine its false-alarm and detection probabilities. The monitor's background determination period is based on observation of background variability and the available time between occupants. The precision of determining background influences the choice of an alarm threshold to meet the prescribed or desired false-alarm probability. For instance, a commonly quoted prescription is one false alarm per 1000 occupants. In this case, a monitor that makes one decision per occupant might have an alarm threshold at 3.1 standard deviations (σ) above the expected monitoring result at background intensity if the background intensity were known exactly. However, imprecise background determination or wide background variability will make a higher alarm threshold necessary in practice to meet any false-alarm prescription.

From our experience we start with an alarm threshold 4σ above the expected background, particularly when we are monitoring pedestrians. The monitoring period is matched to the material detection requirements as follows. We estimate the response of the monitor to the material sample that must be detected and then adjust the length of the monitoring period until the net signal during the monitoring period equals 4σ of the expected monitoring count at background intensity. This defines the alarm threshold for a SIT monitoring system with the required false-alarm probability and 50% probability of detection for the material sample. Of course the choice of 50% detection probability is a matter of convenience and the procedure can be slightly varied to obtain 90 or 95% detection probability.

Besides the SIT, we will discuss one other traditional monitoring technique. The moving-average technique[6] is simply a SIT that is updated at each of four subintervals. It is applied in portal monitors where the subject being monitored is in motion. The moving average matches the counting interval to a time-varying diversion signal that appears when a pedestrian walks through the monitor carrying nuclear material (Fig. 1). The technique samples four times as often as the SIT, hence its alarm threshold is higher for a given false-alarm rate. However, the detection probability at the higher alarm threshold is increased above the SIT by the match between the counting interval and the peak of the diversion signal profile.

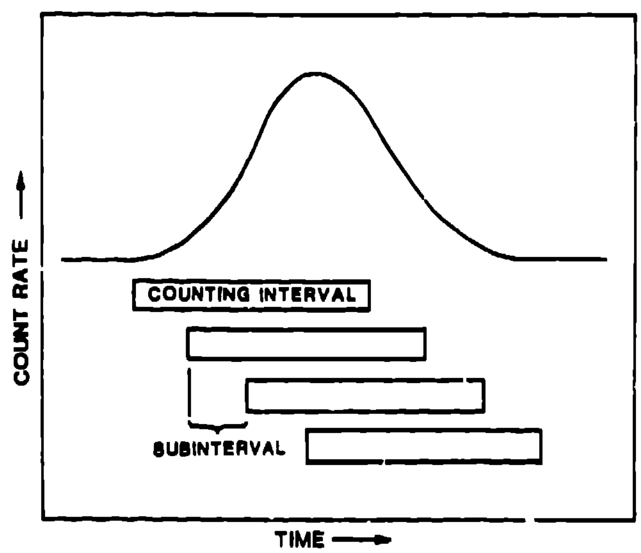

Fig. 1.
The moving-average technique updates the data in a counting interval, after each new subinterval count, by discarding the oldest subinterval data and adding the newest subinterval data. The procedure assures that the peak intensity is concentrated in one counting interval.

HYPOTHESIS TESTING: SEQUENTIAL-PROBABILITY-RATIO TEST

The SIT described in the preceding section can be replaced by a sequential-probability-ratio test that terminates monitoring when a decision is reached rather than always continuing to monitor for a specified time period. We have applied the Wald sequential-probability-ratio test[7] (SPRT) in place of the SIT by dividing a SIT monitoring period into a convenient number of subintervals N and then choosing the other SPRT parameters by analogy to the SIT paramoters. The test, as we apply it, is briefly described as follows.

The Wald test is applied at the end of each subinterval to the data accumulated at that time. The expected value of a subinterval count for background intensity is M0 and for diversion intensity M1. Denoting actual subinterval counting values x_i and the standard deviation of M0 by σ, the logarithm of the ratio of the probability that the subinterval count comes from a diversion count distribution to the probability that it comes from a background count distribution for each subinterval test is defined as Z_i, calculated from the following expression.

$$Z_i = [0.5(x_i - M0)^2/\sigma^2] - [0.5(x_i - M1)^2/\sigma^2] \quad .$$

Estimates of two test thresholds, A and B, are calculated from a false-alarm probability α_0 and a miss probability β_0.

$$A = \log [(1 - \beta_0)/\alpha_0] \quad \text{and}$$

$$B = \log [\beta_0/(1 - \alpha_0)] \quad .$$

At each step in a sequence of subinterval counts, the sum of the Z_i for all completed steps is compared to the thresholds $B \leq \Sigma Z_i \leq A$. The test is terminated whenever ΣZ_i is less than the background inequality at the left or greater than the diversion inequality at the right. Otherwise, as long as a maximum number of steps NMAX has not been reached, monitoring continues with the accumulation of another subinterval count. If no decision is reached after NMAX steps, we record a decision for background.

Values for the parameters in our application of Wald's SPRT are derived from the SIT parameters described earlier in the following manner.

M0 is the expected SIT background divided by N,

M1 is the SIT alarm threshold divided by N,

α_0 is the SIT false-alarm probability disregarding the influence of a short background determination period.

β_0 is 1 minus the SIT detection probability, and

NMAX is equal to or slightly larger than N.

This completes the list of parameters required to replace the SIT or moving average with a SPRT. In some cases we have slightly varied the values of the parameters to make the comparison of SPRT and traditional methods more exact. For example, the diversion threshold value A was decreased slightly in preliminary experiments to match the performance of moving-average and SPRT monitoring techniques. We have carried over that value, 8.0, in later applications of the SPRT monitoring technique to replace the SIT and in all of our Monte Carlo calculations.

Unlike earlier analog applications of SPRT to radiation monitoring,[8] we have implemented the technique in a digital control module that has a microprocessor to carry out the calculations. The controller interprets signals from an occupancy-sensing device near the detectors to tell when background may be measured and when monitoring measurements are required. We report additional information about digital monitor controllers applying the SPRT in Ref. 9.

APPLICATION OF THE SPRT TO VEHICLE MONITORING

Our vehicle monitor described in Ref. 10 originally applied a SIT of 50-s duration. As part of a recent system upgrade, we provided additional detectors and implemented the SPRT for four separate groups of detectors located at different positions in the monitor. Our primary goal for this application of the SPRT was to reduce the monitoring delay while maintaining the best possible detection sensitivity for the available counting time. The original SIT and new SPRT design parameters are compared in Table I.

The expected operational characteristics of the SPRT in the vehicle monitor were determined from Monte Carlo calculations performed on a CDC-7600 computer at the Los Alamos Central Computing Facility. The Monte Carlo program, to be described at the IEEE Nuclear Science Symposium in the fall of 1984, samples from a normal distribution to simulate counting data for the monitoring system which has a Poisson distribution with a large enough mean value to justify the normal approximation. Results were obtained for at least 10^5 trials in each calculation. Two distinct cases were examined: one individual data channel and the combined set of four data channels as applied in the vehicle monitoring system controller. Results for the two cases differ because in the second one, the monitoring result may depend on the outcome of four separate SPRTs. For instance, a diversion decision in any one of the SPRTs will immediately terminate monitoring with a diversion decision, but a nondiversion decision requires a unanimous decision of background for all four independent SPRTs. Hence, the background decision must wait for the slowest SPRT to finish. In all cases, identical radiation intensities are assumed for each data channel in the calculation.

TABLE I
VEHICLE MONITORING SYSTEM PARAMETERS

Parameter	Single-Interval Test Value	Sequential-Probability-Ratio Test Value
Background interval length	100 s	120 s
Monitoring interval length	50 s	48 s
Analogous subinterval number N	1	12
Subinterval length	50 s	4 s
Maximum number of subintervals NMAX	1	15
Value of α_0	3.16×10^{-5}	3.16×10^{-5}
Value of β_0	0.5	0.5

The average monitoring time (AMT) result for the vehicle-monitoring system calculation is illustrated in Fig. 2. The radiation intensity is expressed as a value above background intensity in units of the standard deviation of an expected 48-s-count value at background intensity (σ_{48}). Curve 1a for one data channel has an AMT of about 10 s at background intensity compared to a value of 19 s at the same point on curve 1b for the four-data-channel system. Both values are much less than the SIT monitoring time, which is fixed at 48 s in all cases. Hence, we have achieved our goal of reducing the average monitoring period for most uses of the vehicle monitor. In addition, preliminary experimental results with the new monitoring system indicate that the background intensity is reduced by 1 to 5 % (1.5 to 9.5 σ_{48}) when the monitor is occupied, which may further reduce the AMT (Fig. 3) and alter other operating parameters as well.

The Monte Carlo results in Table II illustrate the influence of more than one data channel and the length of the background determination interval on the false-alarm probability in addition to the monitoring time. Monitoring four channels extends the average monitoring time, but it remains within the time required to obtain exit clearance and is still much less than for the SIT. The influence of the short measurement period for determining the background intensity is considerable, but the result is still close to the usual NRC specification of one false alarm per 1000 passages. In practice, for a vehicle monitor with perhaps only 30 passages per day, the result is quite acceptable for the DOE requirement of one false alarm per day. On the other hand, the background measurement period has little influence on the average monitoring times in Table II or Fig. 3 where that influence was included in calculating the

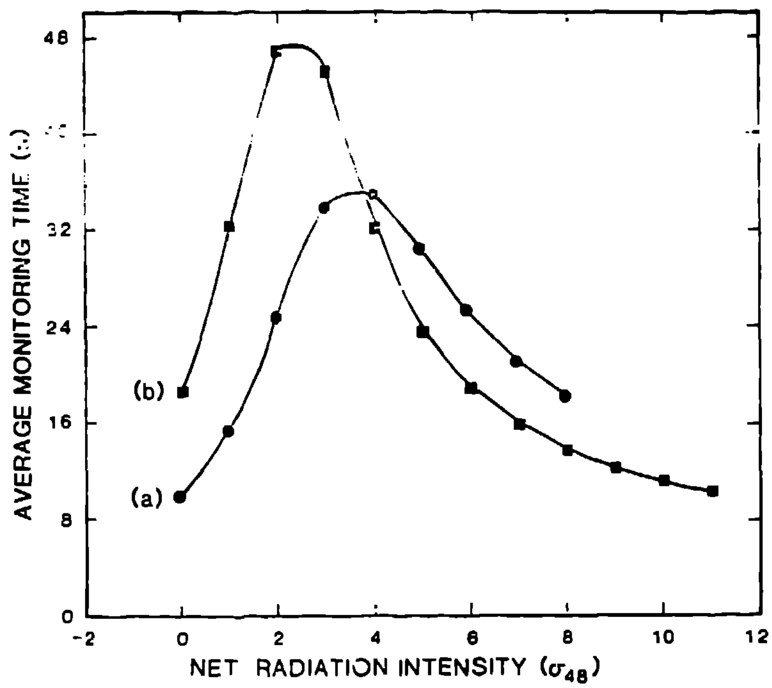

Fig. 2.
The average monitoring time for the vehicle monitor depends on whether (a) a single channel or (b) all four channels must make the final decision. The unit for the radiation intensity is the standard deviation of a 48-s background count. This calculation assumed an exact background mean.

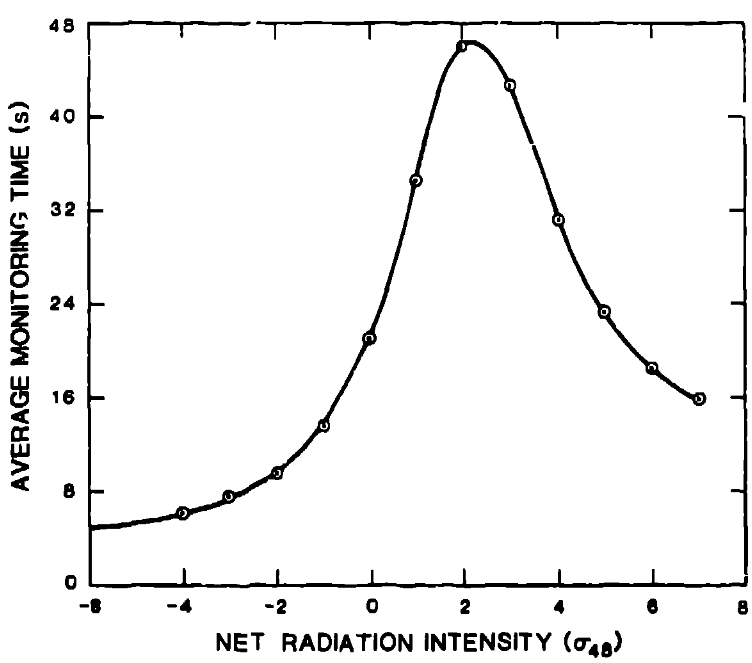

Fig. 3.
The monitoring time may be less when an occupant attenuates the ambient radiation intensity because the average monitoring times are lower below zero, the normal background intensity. This calculation included the normal background determination procedure, which had little effect on the shape of the AMT curve.

TABLE II
MONTE CARLO CALCULATION RESULTS

Parameter	Single-Interval Test Value	Sequential-Probability-Ratio Test Value
Results for an exact background value		
α for one channel	1.1×10^{-4}	1.1×10^{-4}
AMT[a] for one channel	48 s	9.6 s
α for four channels	4.3×10^{-4}	4.3×10^{-4}
AMT[a] for four channels	48 s	19 s
Results with a 120-s-long background interval		
α for four channels	3.5×10^{-3}	3.2×10^{-3}
AMT[a] for four channels	48 s	21 s

[a]Average monitoring time, which is equal to the fixed monitoring time in single-interval tests.

AMT curve. Finally, the operating characteristic for the SIT and SPRT are quite similar (Fig. 4), indicating that the ability to detect diversion is not significantly decreased by the SPRT; the differences would not be discernable on a linear plot.

We varied the values of NMAX and the background-determination interval in some Monte Carlo calculations to determine their effect on the AMT and false-alarm probability. The outcome in Table III at background intensity was that the AMT is little affected by the background interval whereas the false-alarm probability is more dependent on it, as expected. The truncation parameter NMAX influences the false-alarm probability because we always chose the background decision at the truncation point.

At radiation intensities above background, the AMT (Fig. 5) continues to be little influenced by extending the background interval, but the influence of extending NMAX becomes more marked. However, once the radiation intensity passes $3\sigma_{48}$, alarms become frequent, diminishing the need to await four separate decisions and allowing the AMT curves to converge. The

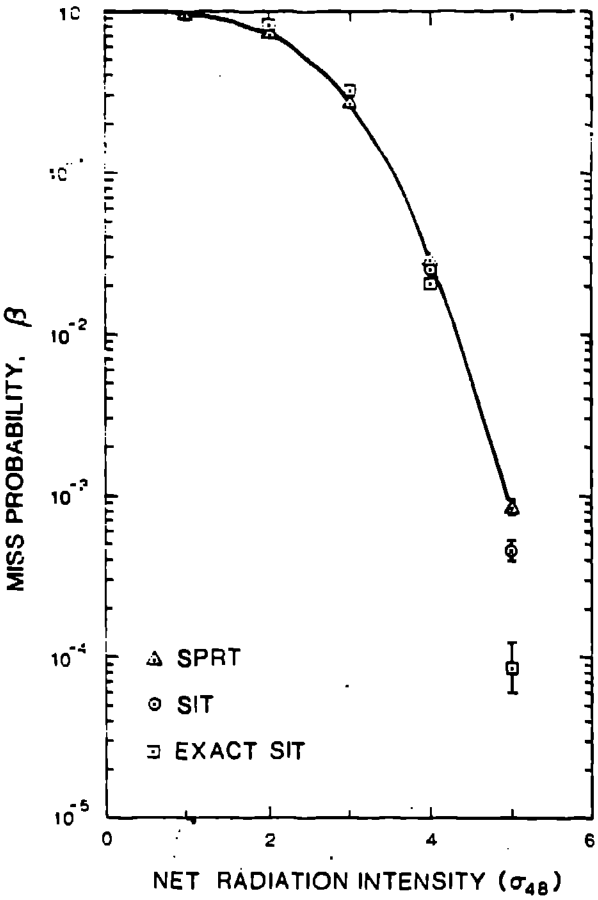

Fig. 4.
The operating characteristic curves for SPRT and SIT are nearly identical with visible deviations appearing only at higher intensities. The actual background determination method is used except for the exact SIT curve where exact knowledge of the background mean intensity is assumed.

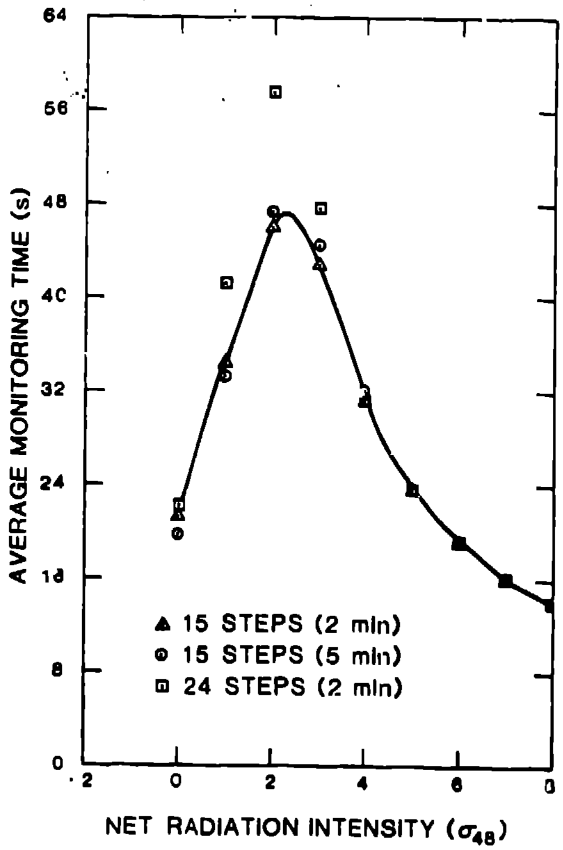

Fig. 5.
The average monitoring time is strongly influenced by permitting more analysis steps before truncating the sequential procedure. The additional time is no longer needed once the radiation intensity reaches the point that a terminating alarm decision becomes more probable.

TABLE III
MONTE CARLO RESULTS AT BACKGROUND INTENSITY
FOR DIFFERENT NMAX AND BACKGROUND INTERVAL

NMAX	Background Interval (s)	AMT (s)	False-Alarm Probability
15	120	21	3.2×10^{-3}
24	120	22	5.4×10^{-3}
15	300	20	1.0×10^{-3}

influence of both parameters on alarm probability continues at higher intensities. The operating characteristic (Fig. 6) illustrates increased alarms over a wide range when NMAX is larger and fewer default background decisions are made. The opposite influence appears when a longer period is available to determine the background intensity.

These comparisons of Monte Carlo results have allowed us to study the effects of changes that might be made in the monitor's microprocessor programs. The effects are difficult to study in the actual monitoring equipment during normal operation because the monitoring periods are so long that a significant number of operational results are impossible to obtain. At this time, we are particularly interested in determining which parameters of the monitoring system may be changed to improve operation and which parameters might be important ones to change to accomodate variation in normal operation. Such variable parameters can easily be incorporated into electrically alterable memory for keyboard modification.

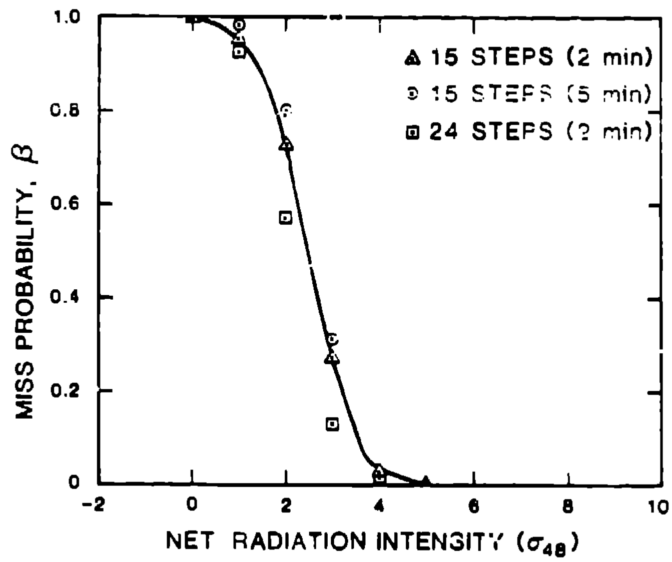

Fig. 6.
The operating characteristic is influenced both by extending the background interval to reduce alarm probability and by extending the monitoring period before truncation.

APPLICATION OF THE SPRT TO PEDESTRIAN MONITORING

Pedestrian monitoring may be accomplished while the subject is stationary or in motion. The former is the more sensitive method and a SPRT can be applied to such a monitor in the same fashion as in the vehicle monitor. However, most pedestrian monitors must, at times, quickly monitor large numbers of people, for instance at the end of a work shift. A walk-through pedestrian monitor is ideal for this application; we have applied the SPRT to such a monitor using the parameters listed in Table IV, and are now investigating its performance.

As in the vehicle monitor, an occupancy sensor notifies the pedestrian monitor's controller that a person is present and to begin monitoring. The person may be stationary or in motion at any speed and he may be anywhere within the sensitivity region of the occupancy sensor. Hence, once monitoring begins it must continue until the occupancy sensor determines that the monitor is again empty to assure that the monitor is not subverted in some way by the occupant. As a result, the pedestrian monitor terminates monitoring in a different way from the vehicle monitor. An alarm terminates monitoring immediately; however, a background decision or reaching NMAX steps simply terminates one sequence and begins another for as long as the monitor is occupied. Another aspect of pedestrian monitoring that differs

TABLE IV
PERSONNEL MONITOR PARAMETERS

Parameter	Sequential-Probability-Ratio Test Value
Background interval length	12.8 s
Monitoring interval length	0.8 s
Subinterval number N	8
Subinterval length	0.1 s
Maximum number of subintervals NMAX	8
Value of α_0	3.16×10^{-5}
Value of β_0	0.5

from vehicle monitoring is that radioactive material passing through the monitor produces a time-varying signal rather than a constant one. As a result, we have not only carried out Monte Carlo calculations at fixed radiation intensities, but also with time-varying signals.

Results for a fixed-intensity, single-interval Monte Carlo calculation for the pedestrian monitor show the same type of dependance of false-alarm probability on the precision of the background determination, as was the case for the vehicle monitor (Table V). The operating circumstances, however, are much more satisfactory, and the relatively short monitoring times allow adequately long background-determination times (12 s) and false-alarm probabilities much closer to the value for an exact background determination. Unlike the vehicle monitor, the short pedestrian monitoring time permits experimental verification of the Monte Carlo calculations. A special monitoring program is easily installed and carries out monitoring repeatedly with periodic breaks for new background determination. Operation is otherwise identical to normal operation and subject to the same background variations. The only difference is that the monitor is always unoccupied. With the special monitoring program we observed a false-alarm probability of 10.6 $\times 10^{-5}$ for 500 000 tests compared to the Monte Carlo value of 6×10^{-5}. This result is reasonable because we know that real background variation takes place from time to time and temperature variation in the detector system can also vary the monitor's count rate somewhat. The AMT for 70 000 tests was 0.193 s, essentially the same as the Monte Carlo result of 0.189 s.

To perform the Monte Carlo calculation for a moving source we established a model for the way the average person would traverse the monitor. We assumed that the occupancy sensor would sense the person and

TABLE V
MONTE CARLO CALCULATION RESULTS FOR THE
PEDESTRIAN MONITOR WITH FIXED RADIATION INTENSITY

Parameter	Background Period	Result
α	exact background	4×10^{-5}
	12 s	6×10^{-5}
	1.2 s	4.7×10^{-4}
AMT[a]	exact background	0.190 s
	12 s	0.189 s
	1.2 s	0.191

[a]Average monitoring time.

begin monitoring 0.4 s before the radiation detectors began sensing the diversion signal. Next, the diversion-signal profile, similar to the one in Fig. 1, would move through the monitor uniformly at a rate corresponding to one of a number of different passage speeds between 0.3 to 2.1 s for complete passage. Finally, monitoring would continue after signal passage for another 0.4 s before the occupancy sensor returned to the empty state. At that point, monitoring could terminate as soon as a decision or NMAX was reached. Of course, a detection at any time during the procedure would terminate that passage and start the next one. The results for this Monte Carlo calculation are in terms of detections and false alarms rather than per test.

Our source profile was determined by moving a source slowly through the pedestrian monitor while recording the radiation intensity and source position. We used a fairly intense source and linearly scaled the measured intensity down to the point that it could be readily detected at normal walking speed, but would not be detected very often at much higher passage speed. Our calculations began at the normal walking speed and progressed through 2, 4, and 8 times normal walking speed. At each speed, we determined the segment of the response curve that would pass through the monitor during each of the 0.1-s counting periods. The average intensity during each segment multiplied by 0.1 s is the net count for that particular step in the Monte Carlo calculation.

Our Monte Carlo calculation results in Table VI are compared to similar results for two other methods, a SIT and a moving-average technique. In each of these techniques we allowed 0.4-s approach and departure times as we did in the SPRT. The counting interval for each of these other methods was also 0.8 s, and the moving average case was subdivided into four subintervals. The

TABLE VI
DETECTION AND FALSE-ALARM PROBABILITIES FOR SEVERAL PASSAGE SPEEDS IN THE PEDESTRIAN MONITOR

Passage Speed	Results for the Indicated Method Detection Probability[a]		
	SPRT	Moving Average	SIT
Normal	0.883 (1.1)[a]	0.970 (1.2)	0.910 (1.1)
Twice normal	0.542 (0.81)	0.588 (0.63)	0.294 (0.78)
Three times normal	0.120 (0.66)	0.095 (0.40)	0.045 (0.56)
Four times normal	0.013 (0.56)	0.010 (0.29)	0.008 (0.56)

[a]Figures in parentheses denote false-alarm probability x 10^3.

SIT covered from 2 to 4 individual tests during the source profile passage whereas the moving average made 3 to 12 tests. Alarm thresholds in each case were adjusted to have identical false-alarm probabilities at background intensity for a normal walking speed passage. The shorter monitoring time for other passage speeds reduced the false-alarm probability per passage, as indicated in Table VI.

The results in Table VI demonstrate improved performance over the SIT in almost all cases for both the moving-average and SPRT methods. It appears that the SPRT is a suitable replacement for both the SIT and moving-average techniques although there is no apparent advantage to the SPRT over the moving average. The SPRT simply exhibits a similar wide adaptability to monitoring pedestrians in motion at a variety of passage speeds that is the forte of the moving-average technique.

SUMMARY

The SPRT provides improved monitoring over the SIT in two applications to material control monitoring, even though the applications require reaching a decision earlier or more frequently than in more usual applications of the SPRT technique. The resulting decreased average monitoring periods in the vehicle monitor are highly desireable and similar results can be obtained with the technique in such other stationary SNM monitors as automated monitoring booths. The application of SPRT to monitoring moving pedestrians achieves

the same advantages over the SIT as does the moving-average technique for which it is a suitable replacement. As yet, we see no advantage for the SPRT over the moving average in performance or hardware implementation but further study may be helpful to clarify this point.

Our experience with Monte Carlo simulation has been a useful one both for selecting operational parameters for the SPRT and for comparing the SPRT to other methods. Our efforts in this regard are still in progress for the monitors discussed in this paper, and we anticipate evaluating new SPRT monitoring systems in the future. One future application similar to that proposed in Ref. 2 will provide longer term monitoring at higher detection sensitivity without the requirement for an immediate decision. In this case, we will determine background from before and after measurements, and process the monitoring results for repeated passages over the course of time for specific individuals or populations. Monitoring will be in parallel with our short-term monitoring system so that not only will fast response be unnecessary, but also anomalously large monitoring measurements can be automatically excluded from the long-term data.

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