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Portal Monitor for Diversion Safeguards

by

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CONTENTS

ABSTRACT	1
I. Summary	1
II. Introduction	1
III. Detection Level and Confidence Intervals	2
IV. Detector Selection	4
A. Radiation Characteristics of SNM	4
B. Figure of Merit for Detector Performance	7
C. Detector Evaluation	7
V. Mechanical Structure	12
VI. Electronic Design	12
A. Requirements	12
B. System Description	13
C. First Generation Warning Logic Module	15
D. Second Generation Warning Logic Module	16
VII. False Alarm Probability	19
A. Calculational Method	19
B. Results	19
VIII. System Performance Tests	21
A. Sliding-Interval Parameter Optimization	21
B. Detection Sensitivity Measurements	22
C. Environmental Testing	25
D. Field Test Experience	27
1. Installation Requirements	27
2. False Alarms	27
3. Film Results	28
4. Alarm Rate Results	28
IX. Portal Monitor Costs	30
X. Conclusions	32
References	32

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ABSTRACT

Two prototype personnel portal monitors were designed, constructed, and tested. These monitors can be used at personnel exits from special nuclear material (SNM) access areas to deter the diversion of SNM. One prototype uses plastic scintillators, the other contains NaI(Tl) detectors. Both units have a digital sliding-interval warning logic system. Detection sensitivities of both units for bare minimum surface-area samples are about 4 g of 93% ^{235}U and 0.1 g of weapons-grade plutonium.

I. SUMMARY

The design, construction, and testing of two prototype personnel portal monitors have been completed. One unit uses four 51-mm-diam by 0.91-m-long plastic scintillator rods; the other prototype contains four 127-mm-diam by 25-mm-thick NaI(Tl) detectors. Commercially available electronic components are used extensively, except for the alarm decision logic. This logic uses a unique LASL-designed, digital, sliding-interval technique. The logic module design and improvements to the original model are discussed in this report.

A detector evaluation program was carried out before choosing the detectors described above. We summarize this evaluation and discuss in Sec. IV the detector selection criteria used.

Tests of the detection sensitivity used plutonium and both enriched and depleted uranium samples in several geometrical configurations. Detection sensitivities for both prototypes were nearly identical, 1 to 4 g for bare ^{235}U samples and approximately 0.1 g for plutonium. The detection sensitivity's dependence on sample geometry and shielding was investigated and is reported in Sec. VIII B.

Field tests at several Los Alamos Scientific Laboratory (LASL) sites are described in Sec. VIII D. These tests provided useful information on false

alarm rates under realistic conditions. In particular, they pointed out the importance of the portal location on the false alarm rate.

Considerable effort was made to minimize the cost of these prototypes. As a result, commercial versions of these designs may cost under \$10 000.

II. INTRODUCTION

In November 1972, the U.S. AEC Division of Nuclear Material Security requested that LASL's Group A-2 review the status of portal monitors specifically designed for domestic diversion safeguards. The request came, in part, because of the close relationship of the portal monitor problem to other on-going work on detectors, data analysis, and perimeter safeguards then under way in the group. Minimal funding was made available for an advanced, broadly applicable doorway personnel monitor design and prototype model to be produced in about 6 months. This report describes the initial design and fabrication of two prototypes as well as subsequent modifications and improvements arising from tests and evaluations done after the first 6 months.

The general objective was to develop further the technology for detecting the concealed special

nuclear material (SNM) on persons exiting from material access areas. A systematic investigation of design parameters during the prototype development, we hoped, would provide suitable performance standards and would lead to a model having adequate sensitivity for plutonium and highly enriched uranium, low equipment and installation costs, minimum interference with normal personnel access, a low false alarm rate, and minimum training for maintenance and security personnel. Design information and improvements developed during the program were provided to interested instrument manufacturers. This was first done in July 1973 through documentation and a demonstration conference. Further information regarding the improvements described in this report was distributed to the same manufacturers in April 1974. Based on results from the two prototypes constructed, minimum performance standards for portal monitors at license-exempt AEC contractor facilities were proposed in December 1973. Although these standards have not been universally accepted, they will be used by Group A-2 for evaluating commercial instruments. AEC criteria currently are being proposed by amendments to AECM 2405, applicable to license-exempt facilities, and to 10 CFR Part 73, covering licensees. A preliminary report of this work was presented at the November 1973 ANS meeting.¹ This preliminary report, essentially unaltered from the ANS presentation, has also been published in the August 1974 issue of *Nuclear Technology*.

III. DETECTION LEVELS AND CONFIDENCE INTERVALS

The statistics of detection will be discussed briefly to define some of the terms that appear throughout this report.

The detector counts observed during a fixed counting interval are statistically distributed and follow a Poisson distribution whose single parameter is the mean value m . The standard deviation σ of a Poisson distribution is $\sqrt{m}$. The Poisson distribution is valid only for integer values of the variable x . The probability of observing x counts when the mean value is m is given by

$$P_x = \frac{m^x e^{-m}}{x!} \quad (1)$$

For values of m of about 30 or greater, the Poisson distribution can be well approximated by the normal or Gaussian distribution with $\sigma = \sqrt{m}$. For the nor-

mal distribution the probability of observing a value lying in dx about x is

$$dP_x = \frac{1}{\sigma\sqrt{2\pi}} e^{-\left[\frac{(x-m)^2}{2\sigma^2}\right]} dx \quad (2)$$

The remainder of this discussion will be concerned with only the normal distribution, because it applies in almost all cases of interest. The probability of observing a value of x that exceeds the mean value m by some arbitrary amount is given by

$$P(x > k) = \frac{1}{\sigma\sqrt{2\pi}} \int_k^{\infty} e^{-\left[\frac{(x-m)^2}{2\sigma^2}\right]} dx \quad (3)$$

Customarily k is given in multiples of the standard deviation σ . The probability of observing a variation above the mean of ≥ 2 std dev is indicated by the cross-hatched area in Fig. 1. Probabilities of an observation x exceeding the mean value m by $k\sigma$ or greater are given in Table I.

In the absence of an external radioactive source, the natural radiation background will produce detector counts in a given time interval whose observed value B is normally distributed about a mean value $\bar{B}$. This case is shown in Fig. 1 and Eq. 2, where B corresponds to x and $\bar{B}$ corresponds to m . The standard deviation of this distribution is $\sigma = \sqrt{\bar{B}}$.

Now assume the presence of a radioactive source that gives a net observed count S , which is also normally distributed about its mean value $\bar{S}$.

Fig. 1.

Distribution of the probability of obtaining a count x that deviates from the mean m by a factor $k\sigma$. Hatched area corresponds to probability of observing a deviation of 2σ or greater.

TABLE I
PROBABILITY OF DEVIATIONS

$k = \frac{x-m}{\sigma}$	Probability
0.0	0.5000
0.5	0.3085
1.0	0.1587
1.28	0.100
1.64	0.0505
2.0	0.0227
3.0	0.00135
4.0	0.0000317
5.0	2.86×10^{-7}

The observed total detector counts $S + B$ are normally distributed about a new mean $\bar{S} + \bar{B}$. Given the observed count $S + B$, we must determine if this represents a statistically significant difference from the mean background $\bar{B}$ to conclude that a radioactive source is present. This is represented graphically in Fig. 2. If the observed count exceeds a chosen detection level L , we have detected a source; and if the count is less than L , a source is not present. This statement can be made only if qualified with the proper probabilities, because two types of errors can occur. Following Altshuler and Pasternack,² we call these Type-I and Type-II errors. A Type-I error occurs when no source S is present, but the background fluctuations exceed the level L . This probability is represented by the shaded area α in Fig. 2 and corresponds to the probability of falsely concluding that a source is present when it is not. We refer to this Type-I error as a statistical false alarm. A Type-II error occurs when a signal is present but the observ-

Fig. 2.
Probability distributions showing Type-I (hatched area α) or Type-II (hatched area β) errors for mean background $\bar{B}$, alarm level L , and mean net signal $\bar{S}$.

ed count $S + B$ is below the detection level L , and it is falsely concluded that no source is present. This probability is represented by the hatched area β in Fig. 2. The area under the $S + B$ curve above the detection level represents the probability $1 - \beta$. This is later referred to as detection probability or detection confidence level.

To express the differences $L - \bar{B}$ and $(\bar{S} + \bar{B}) - L$ in the units of $\sigma = \sqrt{B}$ is common practice. Then tables of the normal probability distribution can be used to evaluate the false alarm probability α and the detection confidence $1 - \beta$ for any selected value of the detection level L and mean signal $\bar{S}$. Implicit in this discussion is the assumption that the standard deviation of the signal plus background distribution $S + B$ is equal to that of the background distribution B . This assumption is valid for reasonably large values of $\bar{B}$, detection levels L that are close to $\bar{B}$, and confidence levels $1 - \beta$ that do not greatly exceed 0.95.

Examples of the use of these concepts follow. The numerical values closely approximate those pertinent to the portal monitors described in this report. Given a mean background count rate of 1200 cps and a counting interval of 0.6 s, then $\bar{B} = 1200 \times 0.6 = 720$ counts, and $\sigma = \sqrt{B} = 26.8$ counts. Assume what we call a 4σ detection criteria, that is,

$$\frac{L - \bar{B}}{\sqrt{B}} = 4$$

then $L - \bar{B} = 4 \times 26.8 = 107.2$, and $L = 827.2$ counts. Thus, anytime a count accumulation greater than 827 is observed in a 0.6-s count interval, we assume that a radioactive source has been detected. The probability that this is a false alarm from statistical fluctuations in the background is given by the area

$$\alpha = P\left(\frac{x - \bar{B}}{\sigma} > 4\right).$$

From Table I this false alarm probability is 3.17×10^{-5} . Because this probability is low, we very likely have detected a source with an observed count of 827 counts/0.6 s. However, we can make numerous assumptions regarding the source strength and its detection probability for the 4σ detection level of 827 counts. Two possibilities are shown in Fig. 3. If the mean value of the signal results in a count of 107.2 counts/0.6 s giving $\bar{S} + \bar{B} = 107.2 + 720 = 827.2$ counts, then a number of trials would give the distribution shown as $S_{50} + B$. The subscript defines the

detection confidence, which is the probability $1 - \beta$ for a source count whose distribution has mean value of $S_{50} + B = L$. This source would be detected with a detection confidence or probability of $1 - \beta_{50} = 50\%$. A stronger source with a total mean count value $S_{95} + B$ will give a detection confidence or probability of $1 - \beta_{95} = 95\%$ if its mean source strength is an additional 1.64σ greater than the 107.2 count source, that is, $S_{95} - S_{50} = 1.64\sqrt{B} = 44$ counts. The 1.64 factor arises from the difference in k between the 50% and 95% probabilities given in Table I. Thus a source with a mean value of $S_{95} = 107.2 + 44 = 151.2$ counts/0.6 s would be detected with 95% confidence. This compares to the mean source strength of $S_{50} = 107.2$ counts, which would be detected with 50% confidence.

In practice the detection level L is generally determined by choosing a tolerable false alarm probability (α of Fig. 2). The specified sensitivity then depends upon the detection confidence desired ($1 - \beta$), as illustrated for two cases in Fig. 3. We have chosen to specify sensitivity at the 50% detection confidence level. The additional source strength needed for 95% detection confidence can be obtained from the 50% confidence value by multiplying it by the ratio

$$\frac{L(\sigma) + 1.64\sigma}{L(\sigma)}$$

where $L(\sigma)$ is the detection level in units of $\sigma = \sqrt{B}$. For example, for a 4σ detection level

$$\frac{4 + 1.64}{4} = 1.41$$

Fig. 3.
Probability distributions illustrating difference between detection of mean signal S_{50} with 50% confidence and detection of mean signal S_{95} with 95% confidence with mean background B and alarm level L .

Thus a source 1.41 times greater in strength is needed for a 95% detection confidence than is required for 50% detection confidence. As noted later, this factor does not always translate directly to source mass, because source strength is not always directly proportional to mass for SNM.

IV. DETECTION SELECTION

A. Radiation Characteristics of SNM

The isotopes to be considered here are ^{235}U , ^{238}Pu , and ^{238}U . The importance of the first two is obvious because of their potential use in nuclear weapons. Uranium-238 is always found with ^{235}U and therefore merits consideration. We will not discuss ^{233}U . It is not yet as common as the other three isotopes, and because of the high gamma activity of ^{233}U and the ^{232}U daughters that are always present, it does not present a difficult detection problem.

Uranium-235. The principal photon emissions from ^{235}U are at 186 keV, and the ever present fluorescent x rays in the 100-keV region. The x rays can be geometry-dependent but are always present in significant quantities in gram-sized samples of all SNM. No important higher energy gamma emissions from ^{235}U occur. Bare samples do not present a difficult detection problem. However, because of its low-energy emissions, ^{235}U can easily be shielded, thereby making passive detection by gamma-ray counting impossible. This strong attenuation is shown in Fig. 4 for two common shielding materials.

Plutonium-239. In addition to the K x-ray complex around 100 keV, ^{239}Pu emits strong lines at 129 keV, 208 keV (from ^{237}U , a ^{241}Pu daughter), a complex of gammas around 400 keV, and weaker gammas in the 600- to 800-keV region. These are all overwhelmed by the 60-keV gamma ray from ^{241}Am (a ^{241}Pu daughter that builds up with age). The ^{241}Am gamma and the strong K x-rays are easily absorbed. However, the large number of gammas above 200 keV are more penetrating and make detection of ^{239}Pu fairly easy even with modest shielding. The ^{240}Pu content of plutonium also provides a neutron source of about 900 n/s/g ^{240}Pu . With the proper detector these neutrons could be used to detect large amounts of heavily gamma-shielded plutonium. We have not pursued this detection mode for the personnel portal, because such a large amount of material and shielding cannot be concealed easily on a person.

Fig. 4.
Photon attenuation (narrow beam) for major emissions of ^{235}U for two common absorbers.

Uranium-238. The major emissions from ^{238}U come from its $^{234\text{m}}\text{Pa}$ daughter, which grows in with the 24.1-d half-life of the intervening ^{234}Th . These emissions include a bremsstrahlung spectrum prominent below 500 keV and low-intensity but penetrating gammas in the 700- to 1000-keV range. Very low-intensity, high-energy gammas up to 2000 keV are generally not of practical use in portal monitoring applications. Of course, the uranium K x-rays are also present.

Table II displays the gamma activity in various energy ranges for these isotopes.³⁻⁵ The age dependence of the ^{238}U daughter gamma activity could present a problem in areas where chemical separations are performed, for example, fuel reprocessing plants and enrichment facilities. Here "fresh" ^{238}U may be found with even less gamma activity than the weak listing in Table II.

Figure 5 shows pulse height spectra from these three isotopes in the 0- to 250-keV range taken with a 127-mm-diam by 25-mm-thick NaI detector. These spectra are shown for illustrative purposes only, and the intensities should not be compared directly because different counting times, samples sizes, and source-detector distances were used. The spectral

shapes, however, are representative of the particular sources and detector used. The features of these spectra are not extremely geometry dependent, because all of these samples were infinitely thick for emissions in this energy range. Comparing Figs. 5

Fig. 5.
Typical pulse height spectra from SNM in 0- to 250-keV energy range. Detector is 127-mm-diam by 25-mm-thick NaI(Tl) with 0.25-mm beryllium entrance window. Samples are right circular cylinders with height equal to diameter.
 ^{238}U — 1002.6-g, 40.6-mm-diam, bare
 ^{235}U — 98.59-g, 18.9-mm-diam, bare
 ^{239}Pu — 0.918-g, 4.31-mm-diam, canned in 0.25-mm stainless steel.

TABLE II
GAMMA-RAY ACTIVITY OF SNM IN SELECTED ENERGY REGIONS

Isotope	Decay Rate (dps/g)	Gamma Activity		Comments
		Energy Range (keV)	(γ /s-g)	
^{235}U	7.997×10^4	75 - 210	6.18×10^4	Does not include geometry-dependent uranium K x rays in 100-keV region, which approximately double the listed intensity if included.
^{239}Pu	2.268×10^9	80 - 770 197 - 451	3.33×10^5 1.34×10^5	Does not include geometry-dependent plutonium K x rays in 100-keV and age-dependent ^{241}Am from ^{241}Pu decay, which dominate the spectrum and overwhelm the listed intensities.
^{238}U	1.244×10^4	80 - 1001 700 - 1001	129 121	Strong bremsstrahlung below 500 keV from β^- of ^{234}Th and geometry-dependent uranium K x rays in 100-keV region not included.

and 6 gives an idea of the relative magnitude of the low- and high-energy emissions from ^{238}U and ^{239}Pu . Some of the low-energy continuum is, of course, scattered radiation from Compton events in the source and detector. The low-energy emissions dominate the spectra, although there are significant contributions from higher energy gammas (>200 -keV) in the ^{238}U and ^{239}Pu spectra. Uranium-235 is not shown in Fig. 6 because it has no significant emissions above 205 keV.

For ^{238}U and ^{239}Pu the intensity ratio of high- to low-energy gammas depends on sample size and configuration because of self-attenuation effects. Ninety-five percent of the infinite thickness emission can be obtained from a sample that is 3-mfp thick for the radiation of interest. This parameter is tabulated in Table III for uranium and several photon energies of interest and is essentially the same for plutonium. Referring to Table III and the Fig. 5 caption, we note that the 1-kg ^{238}U sample used for the spectra of Figs. 5 and 6 is infinitely thick for its 1-MeV emissions,

whereas the 1-g ^{239}Pu sample has somewhat less than infinite thickness for its 400-keV emissions.

The strong self-absorption of the dominant low-energy gamma rays emitted by SNM means that for bare samples of these materials the total source strength is almost entirely dependent on the projected surface area, not the sample mass. This

TABLE III
URANIUM SELF-ABSORPTION

Photon Energy (keV)	Uranium Thickness for 95% of Infinite Thickness Emission Rate (mm)
100	0.85
185	1.07
400	5.64
1000	20.8

Fig. 6.

Typical pulse height spectra showing higher energy emissions from ^{238}U and ^{239}Pu . Samples and detector same as Fig. 5.

becomes important when choosing samples to use in specifying doorway monitor performance.

B. Figure of Merit for Detector Performance

Many variables must be considered when choosing a detector for portal monitoring applications. These variables include intrinsic efficiency, detector geometry, detector size, spectral response characteristics, operational characteristics, and cost. To find a Figure of Merit (FOM) to account for all these parameters is impossible; however, in an operating system the need to minimize that count time can be used to develop a meaningful FOM.

A personnel monitor that does not impede traffic is desirable and is particularly important for large facilities at shift-change times. To be able to pass through a monitor at normal walking speed without pause means that the total time available for a count is ≤ 1 s for a 0.75-m-wide portal.

For given mean signal and background count rates, $\bar{s}$ and $\bar{b}$, the time for detection of the signal, given a detection criteria of net signal counts = $n \cdot \text{std dev of the background counts}$, is:

$$\bar{s}t = n\sqrt{\bar{b}t}$$

$$\bar{s}^2 t = n^2 \bar{b}$$

$$t = \frac{n^2}{(\bar{s}^2 / \bar{b})}$$

The minimum time for detection is inversely proportional to $\bar{s}^2 / \bar{b}$, where $\bar{s}$ and $\bar{b}$ are the mean signal and background count rates. This suggests that $\bar{s}^2 / \bar{b}$ is a useful FOM for detector evaluation, because the larger the value of $\bar{s}^2 / \bar{b}$, the shorter the detection time. We drop the mean value notation for convenience and for FOM purposes adopt the notation S^2 / B .

The S^2 / B FOM accounts for many of the detector variables previously mentioned. The effects of intrinsic detector efficiency, detector size, detector spectral response, and to some extent, detector geometry are included. The parameters of operational characteristics and cost are not included, but using S^2 / B per dollar can account for the cost. For a given detector and sample, S^2 / B itself can be optimized as a function of bias level or single-channel analyzer window settings. Comparisons between detector types are only meaningful if this optimization has been performed on all detectors.

C. Detector Evaluation

We mainly considered two types of detectors, NaI(Tl) and plastic scintillators. For this application, we ruled out the use of liquid scintillators, because we have had problems with leakage from commercially-available liquid scintillators. In addition, we felt that solid plastic scintillators could be used in various geometrical configurations more easily and more cheaply than the liquid types because plastic is easier to "package" than liquid.

Because we had a short time to evaluate plastic scintillator types, we drew heavily on the experience of the personnel at the Dow Chemical Corporation Rocky Flats Plant.⁶ We thoroughly evaluated cylindrical rods of NE-102 (Nuclear Enterprises, Ltd., San Carlos, California) in 25- and 51-mm diameters similar to those Rocky Flats has used for the detection of plutonium. The requirement to build a "universal" portal monitor led us to concentrate on evaluating the detectors for ^{235}U , which presents a more difficult detection problem than plutonium. Almost any detector that does a good job for ^{235}U will be more than adequate for plutonium because of the greater activity and higher gamma energies of ^{239}Pu relative to ^{235}U .

Plastic scintillators are difficult to use for low-energy photons. Their pulse height response to monoenergetic photons consists only of a Compton electron distribution, because their low-Z constituents have no significant photoelectric cross section above 100 keV. The need to bias out the high background and noise at small pulse heights means that many counts are lost from the low-energy (100- to 200-keV) emissions from ^{235}U . This efficiency fall-off at low energies is shown in the efficiency curves in Fig. 7. These data are taken from Roulston and Naqvi,⁷ who claim that measured efficiencies below 200 keV are higher than these calculations, presumably due to multiple scattering. The difficulty in low-energy detection is illustrated by the fact that the maximum electron energy from 100-keV gammas in plastic is only 28 keV and that from 200-keV gammas is only 86 keV. Pulse height spectra from samples of ^{235}U , ^{238}U , and ^{239}Pu , as well as from background are shown in Fig. 8 for a 51-mm-diam by 914-mm-long rod of NE-102 coupled to a 127-mm-long light pipe and an RCA 4523 photomultiplier. These spectra are characterized by a smooth, featureless continuum rapidly rising at low pulse heights. They may be contrasted to the NaI spectra of Figs. 5 and 6. To help evaluate the proper thickness of a plastic scintillator for optimum detection, we also studied 127-mm-diam cylindrical samples of NE-102 in thicknesses of 51 and 102 mm. These were coupled to an RCA 4525 PMT.

From previous experience with NaI(Tl) detectors, we concluded that 127-mm-diam by 25-mm-thick detectors provided a near-optimum compromise detector size for the wide range of energies (< 100 to > 1000 keV) emitted from SNM. Table IV shows the total intrinsic detection efficiency for several promi-

Fig. 7.

Intrinsic detection efficiency as a function of photon energy and detector thickness for a typical plastic scintillator biased at 25 keV.

TABLE IV

TOTAL INTRINSIC DETECTION
EFFICIENCIES FOR 25-MM-THICK
NaI (Tl) DETECTORS

Energy (keV)	Efficiency (%)	Applicable Isotope
100	100	All SNM (K x rays)
185	97	^{235}U
400	65	^{239}Pu
1000	41	^{238}U

nent emissions. These efficiencies may be compared with those for plastic scintillators shown in Fig. 7. The total detection efficiency (as opposed to photopeak efficiency) is the pertinent parameter to tabulate, because wide windows extending from below 100 keV to above the main gamma peaks generally maximize S^2/B for a given source.

The total detection efficiency varies as $(1 - e^{-\mu t})$, where μ is the absorption coefficient and t is the detector thickness. Therefore little is gained in using a detector more than about 1-mfp (equal to $1/\mu$) thick for the radiation of interest. This thickness gives an efficiency of 63%, whereas doubling the thickness increases the efficiency only to 86.5% but greatly increases the cost, which can become an overriding factor in NaI(Tl) systems. Under this criteria a 25-mm-thick detector should be ideal for plutonium, overly thick for ^{235}U , and slightly thin for ^{238}U . However, considering the lower energy bremsstrahlung emissions from ^{238}U , a 25-mm-thick detector is a good compromise for all energies of interest from SNM. This size provides a large detection area (126.7-cm^2) for a relatively low cost (approximately \$625). Its main disadvantages are that its response drops rapidly off axis and that it has the same temperature problems that most NaI detectors have (thermal shock can fracture the crystal).

We looked in less detail at a FIDLER-type⁸ detector [127-mm-diam by 1.6-mm-thick NaI(Tl) with 0.25-mm beryllium entrance window] with the thought that it could be valuable for detecting low-energy fluorescent x rays and scattered degraded energy photons from heavily shielded samples. Proportional counters and Geiger counters were also examined, mainly because of their low cost.

Two commercially available instruments were evaluated for use in this portal monitoring problem. Both the Eberline model PMP-4 Beta Gamma Portal Monitor and the Reuter-Stokes RSS-111 Environmental Radiation Monitor lacked adequate sensitivity,

time response, or both to be applicable. These instruments were not designed for this purpose, therefore this judgment in no way applies to their use in their intended application.

The results of evaluating several detector types with a bare ^{235}U sample are listed in Table V. Clearly the 127-mm by 25.4-mm NaI(Tl) is superior on both an S^2/B and S^2/B per dollar basis. However, this does not tell the whole story, because the cost per unit is about twice that of the plastic scintillators. The total system cost is an important parameter, which can conflict even with a "most detection per dollar" FOM. Because the 914-mm-long plastic rods are used vertically, the response of four such rods covering a 2.1-m-high doorway is fairly uniform, more uniform than that with four NaI detectors that cost nearly twice as much.

Although this table does not show it, the FIDLER NaI was found to be slightly superior to the 127-mm by 25-mm NaI only for the heavily shielded case

(17.6-mm Pb). However, with this shielding, the count rate is so low (see Fig. 4) that with count times of the order of 1 s neither system could detect an enriched ^{235}U sample, so the comparison is academic.

The measured S^2/B values in Table V are optimum values for all detectors listed except for, perhaps, the 25-mm-diam by 914-mm-long NE-102 rod. This value may be nonoptimum, but even a factor of 4 increase does not make it competitive with the 51-mm-diam rod whose cost is nearly the same.

The optimum windows for maximizing S^2/B were determined with the aid of a computer program that listed a cumulative sum of the net signal count rate and background count rate as a function of energy. Subtracting the listings for any two energies gave the S and B for the window defined by those energies. The optimum windows were then found by trial and error.

TABLE V
DETECTOR EVALUATION FOR ^{235}U DETECTION

Detection	Measured S^2/B^a	Estimated Cost ^c (\$)	S^2/B Dollar
NaI, 127-mm-diam by 25.4-mm-thick	35 500	625	56.8
NaI, 127-mm-diam by 1.6-mm-thick (FIDLER)	20 100	1000	20.1
NE-102 127-mm-diam by 102-mm-thick	11 600	285	40.7
NE-102 127-mm-diam by 51-mm-thick	9 860	240	41.1
NE-102 51-mm-diam by 914-mm-long	8 300	350	23.1
NE-102 25-mm-diam by 914-mm-long	660	290	2.3
Geiger Tube (129-cm ²)	40 ^b	60	0.7

^aMeasured with unshielded ^{235}U disk source (51-mm-diam, 0.51-mm-thick, 22-g) 610 mm from detector.

^bExtrapolated from measurement on 15.9-mm-diam by 203-mm active length GM tube.

^cCost includes scintillator PM tube and voltage divider.

The 127-mm by 102-mm NE-102 detector is somewhat better than the 51-mm-diam rod, but suffers one of the same problems as the 127-mm by 25-mm NaI(Tl), that of poor off-axis response.

The comparison of several detector types as a function of sample shielding is given in Tables VI and VII. In Table VI (^{235}U sample) note the very rapid decrease in S^2/B with added shielding. Also, the optimum window changes from 70- to 220-keV for a bare sample to 160- to 220-keV for a shielded sample. Both bare and shielded configurations cannot have optimum detection simultaneously with a single-channel system. A similar effect is seen for ^{238}U in Table VII. Here the fall-off in S^2/B with shielding is less rapid than for ^{235}U because the gammas from ^{238}U daughters are higher energy and more difficult to shield. The lower level setting of the optimum window changes in a continuously increasing manner as the shielding is increased. These data show that for a two-channel system and 127-mm by 25-mm NaI(Tl), nearly optimum detection windows for ^{235}U and ^{238}U can be obtained simultaneously with only one single-channel analyzer (SCA) by setting the SCA window for ^{235}U detection (about 70- to 220-keV for a bare sample) and by using the lower level discriminator output to approximate an optimum window for ^{238}U . In this case the ^{238}U window becomes 70- to ∞ -keV instead of the optimum 13- to 1130-keV, but this only reduces S^2/B by 6%.

For ^{239}Pu the optimum SCA windows vs shielding thickness for a 127-mm by 25-mm NaI(Tl) are given in Table VIII. This table illustrates again how the optimum window changes with shielding. For plutonium a compromise window of 0- to 440-keV does not seriously degrade detection capability for any of the shielding configurations.

A clear-cut choice for a single detector for the portal monitor system did not exist. The advantages of the high intrinsic efficiency and resolved pulse height distribution of NaI are offset by its relatively high cost, sensitivity to thermal shock, and poor off-axis response for the 127-mm by 25-mm configuration. Plastic is less expensive; the rods have a smooth (but not uniform) axial response; and they can be easily made in large cross-sectional areas to compensate for their lower intrinsic efficiency. Small bias level shifts can cause large background changes because of the steeply rising pulse height distribution at low energies (Fig. 8). This disadvantage can be largely offset, however, by using stable electronics and an automatic background updating logic system.

Considering the number of parameters involved, we decided to build both an NaI and a plastic system to compare directly their operation. The NaI system used four 127-mm-diam by 25-mm-thick NaI(Tl) detectors for a detector cost of about \$2500. Although a six-detector version would have greater sensitivity

TABLE VI
DETECTOR EVALUATION WITH SHIELDED
 ^{235}U SAMPLE^a

Detector ^c	S^2/B for Given Sample Shielding ^b		
	Bare	1.6 mm Pb	3.2 mm Pb
127-mm by 25-mm NaI	35 500 (70-220)	313 (160-220)	9.19 (160-220)
127-mm by 1.6-mm NaI (FIDLER)	20 100 (15-220)	64 (9-220)	2.1 (9-220)
127-mm by 102-mm NE-102	11 600 (11-115)	79 (12-160)	2.0 (12-160)
127-mm by 51-mm NE-102	9 860 (12-125)	48 (11-138)	1.4 (16-138)

^aSample is (51-mm-diam, 0.51-mm-thick, 22-g) 93% ^{235}U , 0.94 m from detector face.

^bNumbers in parentheses are optimum energy windows for maximum S^2/B given in keV photon-energy for NaI and keV recoil electron-energy in detector for NE-102.

^cUnshielded.

TABLE VII
DETECTOR EVALUATION WITH SHIELDED ^{238}U SAMPLE^a

Detector ^c	S^2/B for Given Sample Shielding ^b				
	1.6 mm brass	1.6 mm Pb	3.2 mm Pb	6.4 mm Pb	12.7 mm Pb
127-mm by 25-mm NaI	552 (13-1130)	152 (210-1130)	100 (260-1130)	47 (318-1130)	12 (318-1460)
127-mm by 51-mm NE-102	205 (17-857)	78 (74-857)	53 (95-857)	27 (116-857)	7.7 (131-907)
127-mm by 102-mm NE-102	243 (25-857)	96 (87-857)	68 (110-895)	36 (126-895)	11 (131-895)

^aSample (51-mm-diam, 2.5-mm-thick, 104-g) ^{238}U disk 0.416 mm from detector face.

^bNumbers in parentheses are optimum energy windows for maximum S^2/B given in keV photon-energy for NaI and keV electron-energy in detector for NE-102.

^cUnshielded.

and more uniform vertical response, it was rejected because of cost. The plastic scintillator system used four 51-mm-diam by 914-mm-long rods of NE-110. NE-110 was used instead of NE-102 because of its better light transmission characteristics even though it is more expensive. However, we do not feel that it gave any significant improvement over NE-102 in this geometry. Each rod was coupled to a 127-mm-long light pipe and an RCA 4523 PMT. The total cost for these four detectors, including tube bases and

voltage dividers, was about \$1450 (for NE-102), over \$1000 less than the NaI(Tl) system.

TABLE VIII
OPTIMUM WINDOWS FOR 127-MM-DIAM BY 25-MM-THICK NaI AND ^{239}Pu SAMPLE^a

Sample Shielding	Optimum Window (keV)
Bare	13-130
3.2-mm brass	13-440
0.79-mm lead	320-440
1.59-mm lead	320-440
3.18-mm lead	320-440
6.35-mm lead	320-440
12.7-mm lead	13-480
19.0-mm lead	13-250

^aSample (9.82-g of 93.81% ^{239}Pu) is right circular cylinder of height = diam = 9.27 mm, canned in 0.25-mm-thick stainless steel.

Fig. 8.
Typical pulse height spectra from a 51-mm-diam by 914-mm-long rod of NE-102 plastic scintillator. Sources are the same as Fig. 5.

The detector cost for a plastic system consisting of six 127-mm-diam by 102-mm-thick NE-102 cylinders would be about \$1700. We felt the major advantage of the plastic scintillator should be its low cost and thus rejected this higher priced version, even though it appeared that such a system might outperform the rods.

V. MECHANICAL STRUCTURE

The freestanding doorway structure is constructed of four pieces of polyurethane foam, cut from two pieces 10-cm-thick by 2.44-m-long by 61-cm-wide. Provisions are also available for positive floor mounting without the floor plate shown in Fig. 9. The foam pieces are bandsawed to external dimensions, then shaped internally for the hardware with a simple rasp bit in a drill press or hand drill. An interior width of 69 cm was used for the NaI doorway, whereas the plastic doorway's was 76 cm.

The assembly of the portal monitor components in the foam structure is shown in Figs. 10 and 11. After

the equipment is sandwiched in the foam halves and padded with foam rubber to prevent mechanical shock, they are joined with epoxy resin over the fiber-glass cloth. Cable junctions are made in a metal box that mounts between the two frame halves and screws into glassed-over metal plates. Two coats of highly reflective white paint are rolled on over the glass cloth for an inexpensive but rigid, insulated package.

VI. ELECTRONIC DESIGN AND CONSTRUCTION

A. Requirements

The electronic system was designed to minimize routine interactions between the inspector at the portal and the system by automatically updating the warning level generated from average values of the background. The only interaction required is the appropriate response by the inspector when a warning occurs as a person walks through the doorway.

A digital rather than analog logic system was chosen for several reasons.

(1) A digital system provides more inherent stability with no dc levels to drift.

(2) It can perform a moving average to eliminate the need to start the count interval with a flow switch, light beam, or other sensor.

(3) It can accurately generate a warning level of some n standard deviations over a large dynamic range of counts per interval. The warning level provides proper operation over varying background count rates and allows the basic logic system to be used with a variety of detector types and sizes of detector arrays. The user must modify the expected detection probability and statistical false alarm rate if the average count per interval falls below about 30 counts, because below this value the probability of an expected count does not follow the Gaussian distribution.

We have designed a system that provides a warning output if the count C in an interval is $C > \bar{B} + n\sqrt{\bar{B}}$, where $\bar{B}$ is the average background and n is the number of standard deviations. A further design goal was to allow normal personnel traffic and to provide a radiation monitor that ran continuously rather than only when occupied. By generating a moving average of the count, we are assured that the counting interval will span the peak count rate when a person walks through the doorway with a source.

The digital logic system has had several design changes. Two units of the first generation logic system were built and tested, and extensive

Fig. 9.
Complete doorway monitor system.

Fig. 10.
Assembly of plastic scintillator doorway monitor.

measurements on complete doorway monitors were carried out with them. The results of these tests are discussed later. The experience gained with this system was used to simplify the design and eliminate some of the problems found during testing. The second generation logic evolved from these improvements, and the principles of its design are discussed in this section. Laboratory bench models have been built, but the second generation logic has not yet been integrated into a doorway monitor system. The first generation system is also described to illustrate the differences between the two logic systems.

B. System Description

A diagram of the doorway monitor system is shown in Fig. 12. The four detectors are connected to a single high-voltage power supply with individual detector gain adjustments made at the photomultiplier bases. Commercial photomultiplier high-voltage power supplies are satisfactory. We chose a Power Designs AEC-315B.* The resultant signals from the detectors are led through an ORTEC 113 scintillation preamplifier. Two preamplifiers are

*Although we give the specific models used in our system, equivalent ones are available from other manufacturers.

*Fig. 11.
Assembly of NaI(Tl) doorway monitor.*

used, one on each side of the portal, each serving two detectors. These two signals are in turn fed to an ORTEC 485 amplifier for further amplification and shaping. The amplifier output is fed to an ORTEC 406A SCA, which has a lower level discriminator (LLD) output and a window output. These outputs are logic signals representing all detected counts that exceeded the lower level threshold and all detected counts that exceeded the lower level discriminator but did not exceed an upper level discriminator. These logic signals are then fed into each of two channels of the LASL-designed logic module. The 406A LLD and SCA outputs had to be modified to increase the output amplitude from the normal +5V to $\approx +6.5V$ to be compatible with the LASL module logic level requirements.

A light source on one side of the doorway and a photocell positioned on the other side provide a

signal to the logic module, indicating that the doorway has been occupied. This signal is also fed to the logic module, which provides an output alarm signal to expose a single frame in the Kodak Analyst Surveillance camera if the count in either of the two channels exceeds the stored warning level by one or more counts. Alarms occurring within 1.25 s after the first alarm are suppressed because the camera can only take single frames at the rate of 0.8/s. If the doorway is occupied during an alarm, then a signal will also activate a visual and audible alarm. Note that both an occupied signal and a radiation signal are required before the inspector is alerted. If an alarm occurs while the light beam is interrupted, a holding circuit disables the automatic background update feature for 60 counting intervals. This allows the inspector to recheck the suspect by having him

Fig. 12.
Block diagram of the doorway monitor system.

pass through the monitor again against the same background, which he apparently exceeded on the first passthrough. If it is necessary to hold the suspect in the monitor, a dc inhibit feature also continuously inhibits background updating for as long as the light beam is continuously broken.

C. First Generation Warning Logic Module

The first generation logic module has two channels for the two signal inputs. To describe the system shown in Fig. 13, we will follow a signal through channel one.

The incoming signal goes to the signal toggle and through a gate to the sliding-interval counter. The gate is normally open except when the system is reset. At reset the signal is inhibited until a background is stored to suppress an initial series of false alarms. At the signal toggle, the signals from channel one and channel two are alternately fed to the $\bar{B} + n\sqrt{B}$ scalars. If this count is less than an internally selectable prewired value of $(2^5, 2^6, \dots, 2^9)$, a lower level warning is activated. Likewise, an upper level warning is activated if the count exceeds an internally selectable prewired value of $(2^{10}, 2^{11}, 2^{12})$.

The background signals are toggled to the warning-level generator because of the number of integrated circuits required. The warning level, consisting of the $\bar{B}$ and $\sqrt{B}$ in serial binary form, is then transferred to a buffer storage for use until it is updated. The accumulation period for the stored war-

ning level can be internally selected from $(10, 20, \dots, 90) \times T$, the major count interval, and automatically updated every $(10, 20, \dots, 90) \times 2T$. The major count interval T is composed of 9 subintervals τ where τ can be internally selected over a range of 0.065 to 0.162 s in 7 unequal increments. The conditions we have extensively used for testing the first generation system are $\tau = 0.065$ s, background accumulate period $= 30T = 17.5$ s, and a background update period of 35 s. When the $\bar{B}$ and $\sqrt{B}$ are shifted out of the buffer storage to the compare logic, the $\sqrt{B}$ is offset by the number of bits required to accomplish the $n\sqrt{B}$ multiplication.

The other route for the incoming signals to the sliding interval counter goes to a binary counting register. At the end of each subinterval (τ) the contents of this register are parallel loaded into a parallel-in/serial-out shift register. These are then shifted out into another shift register that is nine shift registers (τ 's) long, which acts as a memory, then to a serial adder and to a gate. The gate opens with a period equal to the major counting interval (T), and the adder contents are then shifted out concurrently with the same count that shifts out of the memory shift register. A bit-for-bit comparison is made to insure that no bit errors occurred in the memory shift register. The serial word coming out of the first shift register is the most recent, or C_{i+8} ; and the count coming out of the memory shift register is C_i , or the count recorded a time 9τ earlier. The difference $(C_{i+8} - C_i)$ is fed to an adder and is added to the sum stored in the accumulator. The number stored in the accumulator is the moving average over the last 9τ . This moving average and the generated warning level are compared in a bit-for-bit serial compare system. If the count exceeds the warning level by one or more counts in channel one or channel two, an internal alarm occurs. This causes a photograph to be taken of the doorway unless another alarm occurred no greater than 1.25 s prior to the current alarm, in which event the current alarm is suppressed. Assuming that the alarm is not suppressed and the doorway is occupied, then an audio and visual alarm is activated for the inspector, and the background update is inhibited. This locks the background at the value prior to the alarm and permits the inspector to have the individual walk through the doorway several times without changes in the stored background.

During the design, construction, checkout, and field tests of the system, several deficiencies in this first generation system became evident. The warning level, $\bar{B} + n\sqrt{B}$, is not updated as often as desirable to accommodate a fluctuating background because only one warning-level generation system serves the

Fig. 13.
Block diagram of the doorway monitor's first generation warning logic module.

two channels. The upper and lower level count warning feature has been useful, but a limitation results from having this feature in the common $\bar{B} + n\sqrt{B}$ scalars. The lower level count monitors the higher count channel with less sensitivity, and the upper level count monitors the lower count channel with less sensitivity. These problems can be alleviated by having a $\bar{B} + n\sqrt{B}$ scaler for each channel.

Another problem that became evident regarded the generation of the moving average through the use of an accumulator. Any errors that might be induced by external rf noise or an exceedingly high count rate, which causes the accumulator to overflow, will be retained until the system is reset. This can be corrected by a system that does not use an accumulator.

The audible and visual warning signals and the camera-activation signals have performed as desired.

D. Second Generation Warning Logic Module

To simplify the design and eliminate some of the deficiencies noted in Sec. VI. C, a bench model of a new system was designed and built for doorway monitor applications. The production of the square root in both the first and second generation systems is based upon principles presented in the work of Rao et al.⁹ and Taylor et al.¹⁰

A diagram of a binary rate divider is shown in Fig. 14. Assume a number D is stored in the divisor

Fig. 14.
Block diagram of binary rate divider.

register, and the count register is initially at zero. The input counts are counted until the contents of the count register equal D . At that time the comparator emits a pulse that resets the count register and provides an output pulse. The output count rate C_o is then equal to C_i/D .

Connect the divisor register to the output count rate as shown in Fig. 15. The input count in a certain time is

$$C_i = \sum \Delta C_i$$

In this time, the output ΔC_o is summed in the divisor register giving

$$C_o = \sum \Delta C_o$$

Thus, the output count increment is

$$\Delta C_o = \frac{\Delta C_i}{C_o} \quad \text{or} \quad \Delta C_i = C_o \Delta C_o$$

Fig. 15.
Block diagram of a binary rate divider connected to provide a square-root extraction.

If we consider these as infinitesimal increments and integrate, we have

$$\int_0^{C_i} dC_i = \int_0^{C_o} C_o dC_o$$

and

$$C_o = \sqrt{2C_i}$$

Thus the square root of twice the input count is stored in the divisor register. If we then modify the circuit in Fig. 15 to that shown in Fig. 16, by dividing by two in the input count line

$$C_o = \sqrt{C_i}$$

Thus we have a simple means of generating the square root of the count in an interval. This does require that an initial condition of a one be stored in the divisor register and that the divide by two and count register be reset to zero. The circuit, similar in principle to the first generation logic system, is much simpler and requires fewer integrated circuits. The first generation system did not reset the count register and therefore required a number of storage latches and adders to predict the next count register number, having a square root one greater than the current square root.

Next consider the generation of a moving average, shown schematically in Fig. 17. The object is to sum the counts over a major interval T and generate a new sum every τ . Analysis of experimental data (see Sec. IX. A) has shown that $\tau = T/4$ is about optimum. Consider a count register as shown in Fig. 18, which is parallel loaded into a parallel-in/serial-out

Fig. 16.
Square-root logic.

Fig. 17.
Sliding-interval technique.

shift register. After loading into the shift register, the contents are shifted out with an appropriate shift train into a serial adder and into a second shift register. Concurrently the output of this shift register is fed to the other input of the serial adder. In the same manner the sum from the adder is added to the contents of the third shift register; and, likewise, this resultant sum is added to the output of the fourth shift register. The final output sum is the moving average of four subintervals.

This system is also similar to the first generation system except it does not have an accumulator. Thus no subtractions are required and no problems of accumulator overflow exist. We accomplished a binary subtraction in the first system by inverting the subtrahend and adding it to the minuend; the resultant

Fig. 18.
Moving average counter.

number was the difference minus one. The difference was then obtained by adding one to the resultant number.

The moving average count must be compared with the warning level. The first generation system compared the two numbers with separate, exclusive ORs, NANDs, etc. In the second-generation system we used a serial adder and one inverter, illustrated in Fig. 19. The carryout of the output will remain high if $C > B$. For example, assume that

$$B = 5_{\text{decimal}} = 101_{\text{binary}},$$

and

$$C = 6_{\text{decimal}} = 110_{\text{binary}}.$$

Now $\bar{B} = 010$ and $\bar{B} + C$ would be

$$\begin{array}{r} 010 \\ + 110 \\ \hline 1000 \end{array}$$

carryout

The carryout is high. Now if $C = 4$, then $\bar{B} + C$ is

$$\begin{array}{r} 010 \\ + 011 \\ \hline 0101 \end{array}$$

carryout

and the carryout is low. Likewise, if $C = 5$ the carryout is also low. A warning is produced from this comparison if $C > B$ by one count. Note, however, that we can use only the carryout, not the complete output.

The other items needed in the warning generation are the multiplication of the square root of the average background by n , the addition of $n\sqrt{B}$ to the average background, and the generation of a serial word. One may, of course, easily multiply a binary

Fig. 19.
Comparison logic.

number by shifting the parallel load into the parallel-in/serial-out shift registers. In Fig. 20 the separate building blocks are put together.

VII. FALSE ALARM PROBABILITY

A. Calculational Method

When the sliding-interval technique was first proposed, the effects of correlated false alarms on the total false alarm rate were questioned. The calculations described in this section were performed to analyze this effect. The entire discussion in this section relates to statistical false alarms that are registered only internally in the doorway monitor system. In addition, occupancy is required before audible and visual signals are given.

Suppose the expected background count in a counting interval T is $\bar{B}$. At the end of each consecutive counting interval, the actual number of counts accumulated C is compared with $\bar{B}$, and an alarm occurs if the net count $C - \bar{B}$ exceeds some selected alarm level.

The ambient background count rate is described by the integer Poisson distribution, which is characterized by one parameter, the value m . The expected background count in T is used as the mean value, and the alarm level is chosen as some number of standard deviations ($\sigma = \sqrt{m}$). The alarm probability for the consecutive interval case can then be readily determined by evaluating the Poisson distribution probability for variations from the mean of this number of standard deviations.

The first problem in using the sliding-interval method is to determine how these alarm probabilities compare with those for the consecutive-interval method for the same total counting time. To evaluate alarm probabilities for the sliding-interval case, the background counting procedure was simulated by

using Monte Carlo sampling methods. For each subinterval τ_i , the background count C_i is determined by sampling from the Poisson distribution using computer-generated random numbers. The sampling algorithm by Knuth¹¹ was used in these calculations. With this sampling method, alarm probabilities were calculated for both the consecutive and sliding-interval methods, using 5, 10, and 20 τ -subintervals per T -interval with alarm levels of $(C_i - \bar{B}) > 2, 3, \text{ and } 4 \sigma$. All calculations are based on a fixed background of 1000 counts per time interval T . This background was not considered to be statistically variable. These calculations showed that for a given alarm level, the alarm probabilities are the same for the sliding-interval and consecutive-interval methods and are independent of the number of subintervals. Because there are n τ -subintervals per T -interval, the sliding-interval method makes n -times the number of alarm tests as the consecutive-interval method. The equal probabilities mean that the number of alarms occurring with sliding intervals is n -times the number with consecutive intervals for the same total counting time, an obvious disadvantage of the sliding-interval technique.

B. Results

Alarm probabilities for 2-, 3-, and 4- σ deviations calculated for the sliding-interval method are given in Table IX. Statistical uncertainties and computational uncertainties associated with application of the sampling algorithm result in errors less than $\pm 10\%$ in the calculated probabilities. This is verified by comparing these calculated probabilities to the probabilities expected from the normal approximation to the Poisson distribution valid for this case.

A single large-amplitude spurious signal can result in n alarms, because this single large signal will be included in n alarm tests. This causes an erroneously high number of alarms to be detected. Several closely spaced spurious signals will result in additional false alarms. To reduce the occurrence of these extra alarms, a sliding-interval detection method with count suppression can be used. When an alarm is detected, the data accumulation is suppressed for the next n subintervals, then the counting and alarm testing continues in the usual manner. This technique will eliminate the next $n-1$ alarms that would otherwise be caused by the single large count. The count suppression will also result in the second of two true alarms not being counted, if the two occur in a time interval shorter than the counting interval $n\tau = T$.

TABLE IX
FALSE ALARM PROBABILITIES FOR SLIDING-INTERVAL METHOD

<u>Alarm Level</u>	<u>Calculated False Alarm Probability</u>	<u>Expected Probability Normal Distribution</u>
2σ	0.022	0.0227
3σ	0.0014	0.00135
4σ	0.000034	0.0000317

Alarm probabilities for the sliding-interval method with suppression were calculated using the same sampling techniques discussed previously. Whenever the normal distribution provides a sufficiently accurate approximation to the Poisson distribution, sampling with the normal distribution will reduce computing time by a factor of about 5. The normal distribution sampling algorithm¹⁰ is inherently faster than the Poisson algorithm. Alarm probabilities for the sliding-interval method with suppression were computed by sampling from normal distribution and are given in Table X. These probabilities are a function of the number of subintervals, whereas the values without suppression (Table IX) are independent of the number of subintervals.

Uncertainties in these alarm probabilities vary from $\pm 5\%$ at 2σ to about $\pm 20\%$ at 4σ . Figure 21 compares alarm probabilities with suppression to the corresponding probabilities without suppression. The

ratio of probability with suppression to probability without suppression is shown as a function of alarm level. For a given number of subintervals, the probability with suppression approaches the probability without suppression as the alarm level increases. This is expected, because fewer alarms occur at higher alarm levels. Less chance exists for a second alarm to occur within the interval $n\tau = T$, which is the necessary condition for suppression. A similar effect explains the decrease in probability ratio for a given alarm level as the number of subintervals increases. With a larger number of subintervals, the chance for more than one alarm to occur is greater within the interval $n\tau = T$, hence suppression is more frequent than with a smaller number of subintervals. For conditions similar to those we have extensively used in the first generation logic module, (that is, $\sigma = 4$, and suppression of 9 subintervals) the effect of suppression as shown in Fig. 21 is about a 20% reduction in the false alarm rate.

TABLE X
FALSE ALARM PROBABILITIES FOR SLIDING-INTERVAL METHOD WITH SUPPRESSION

<u>Alarm Level</u>	<u>Subintervals, n</u>	<u>False Alarm Probability</u>
2σ	5	0.0117
	10	0.0073
	20	0.0041
3σ	5	0.00095
	10	0.00065
	20	0.00040
4σ	5	0.000024
	10	0.000017
	20	0.000013

Fig. 21.
Effect of suppression on false alarm rate.

In the first-generation logic module built for the two prototype doorways, nine 65-ms τ subintervals make up one 585-ms T interval. The alarm sampling rate per hour is therefore $3600/0.065 = 55\,385$. For a 4σ alarm level the hourly alarm rate per channel expected from background statistics alone would then be $55\,385 \times P(4\sigma)$. Taking $P(4\sigma)$ from Table X to be 3.17×10^{-5} , 1.76 false alarms/h/ch are expected. However, the $P(4\sigma)$ value from this probability table is not proper, because the value of B used for the background comparison check changes each time the background is updated. B is not a constant, as was assumed in the previous calculations.

To evaluate further this effect on the false alarm rate, additional calculations were performed that more realistically mocked up the operation of the first generation logic module. The logic module simulation code used a Monte Carlo normal distribution random number generator to produce the required samples. These were accumulated, as in the first generation logic circuit, into 9 sample sums and 270 sample background sums. The program followed the single-channel circuit logic in updating sample sums by dropping the earliest entry when adding the next one and by replacing the background every 540 samples with a new one. The test level used was 4σ , and resultant $P(4\sigma)$ for 3.25×10^5 samples was found to be 2.8×10^{-5} . The calculated statistical false alarm rate is then $55\,385 \times 2.8 \times 10^{-5} = 1.55/\text{h/ch}$.

The false alarm rate was also determined experimentally for the unoccupied doorway by tallying false alarms during periods when the background was known to be free of the fluctuations caused by

normal research activity at the site. The NaI system was monitored for a period of 385.5 h during which the alarms in the two-channel logic module occurred at a rate of 3.30 per h. The plastic system had an intermittent defect which tended to cause spurious alarms, so the period of normal, quiet operation was only 84.5 h. During this time the rate was 1.45 per h for the single channel used. Thus the false alarm rate for the first generation logic appears to be a nominal 1-1/2 per channel per h at a 4σ level. The audible alarm rate from this source would, of course, depend on the fraction of the time the doorway is occupied.

VIII. SYSTEM PERFORMANCE TESTS

A. Sliding-Interval Parameter Optimization

The first generation logic module was designed and constructed before we had determined the best values for the number of subintervals and the major interval time. The following discusses the procedure used to fix the values of these parameters. The results were used in the design of the second generation logic module.

To determine the ideal major counting interval and the optimum number of subintervals for the logic package, measurements were made during simulated usage of the unit. These measurements were subsequently analyzed with a variety of parameters to determine the optimum values of the subinterval number and the major counting interval.

The data were collected using both doorways with sources and source locations, which resulted in a near 50% detection probability for the existing first generation logic module parameters. The procedure used was to multiscale the SCA output as the doorway was repeatedly traversed by a source-carrying individual. Subsequently, a computer program that simulates the logic module operation was used repeatedly to examine the data while varying the major interval time, number of subintervals, and $n\sigma$ detection level. A constraint on the parameter variation was that the false alarm rate from statistical fluctuations should remain constant. That is, as the number of subintervals increased, $n\sigma$ was also increased to achieve the identical statistical false alarm rate.

Figure 22 shows the results used to determine the optimum counting interval. The number of alarms detected is plotted against count interval, and a maximum is clearly shown at 0.8 s. Similar plots at different $n\sigma$ detector levels show similar results. Figure 23 shows the results for the number of alarms

Fig. 22.
Number of alarms detected vs counting interval.
The number of subintervals was fixed at 4 and a 4σ detection criterion was used.

with a 1-s counting time as the number of subintervals is varied. With the addition of the first few subintervals an immediate increase of about 30% results after which no advantage is realized from additional subintervals. In fact, using more than the optimum number of subintervals increases the false alarm rate at a fixed detection level, which is, of course, undesirable.

The optimum parameters for this doorway geometry are an 0.8-s counting time and 4 to 6 subintervals. These parameters (especially the major count interval) would vary for different doorway sizes.

Whereas the nine subintervals used by the first generation logic module is clearly nonoptimum from a false alarm standpoint, the 0.585-s major count interval is not too far from the 0.8-s best value. The se-

Fig. 23.
Number of alarms detected vs the number of subintervals in a 1-s count interval. The false alarm rate is held constant resulting in an no variation from 3.39σ to 4.14σ over the curve.

cond generation logic can be set at the optimum values of a 0.8-s major interval and four subintervals.

B. Detection Sensitivity Measurements

To be able to give an indication of the minimum quantity of enriched uranium or plutonium that can be detected by the portal monitor, several parameters must be considered and defined. First, the confidence level must be decided. Values of 50% or 95% confidence are commonly used. We have chosen 50% for convenience in the evaluation. Thus the mass quoted is the minimum quantity that would be sensed by the monitor on an average of one-half of the passages.

Next, one must consider the way the source is transported through the doorway. A person's speed as he passes through the portal can be expected to vary from hesitation in the portal to a very fast walk. Presumably, in actual use, an individual would be restrained from running by the attendant. Rather than attempting to average the range of sensitivities corresponding to walking rates, we left it to the person carrying the source to walk at an average pace. The test and evaluation data therefore were acquired at walking speeds that varied over values considered average by the personnel involved.

The position of the source in the doorway is also important because of the spatial variation in portal sensitivity. Figure 24 shows measured count rate profiles in the center plane of each doorway. The profiles demonstrate the differences in sensitivity of the two doorways. The sensitivity also varies from side-to-side in a horizontal plane; however, sensitivity generally increases toward the sides of the doorway in any horizontal plane. The position of the

Fig. 24.
Count rate profile measured in the center vertical plane of each doorway using a 21-g ^{235}U disk source, 0.5-mm-thick.

source on the body is another important factor. The rate of passage of the source can vary, for example, by holding a source in the hand and rapidly swinging the arm through the portal. We have chosen to place the source on the body in a realistic manner; that is, we do not consider the source in the hand with the arm outstretched overhead; we do not consider throwing the source through the doorway; and we eliminate other unusual acts, all of which are unlikely to take place at an attended station. We chose to determine the sensitivity for four positions on the body, which we felt are likely hiding spots and are well distributed over the portal aperture. These positions were the top of the head, shirt pocket, side pants pocket, and the inside side of the shoe. The minimum sensitivity areas of both doorways are well covered by this distribution, and an average of the sensitivity for the four positions will allow comparison between the two doorways.

The sources used to determine the doorway sensitivity must have a well-known composition, since the composition can affect the gamma-ray activity. The source geometry can also affect the results of testing, because self-absorption in the source is important at the gamma-ray energies considered here. The composition of our sources was chosen to represent weapon-grade material in the case of ^{235}U and ^{239}Pu , and depleted uranium for ^{238}U . Isotopic analyses are shown in Table XI. The ^{235}U analysis shown here for the cylinders is probably similar to that for the few noncylindrical ^{235}U sources used. The source geometry we chose to use is a cylinder with height equal to diameter. Self-absorption for such geometry is nearly as great as for a sphere, but the geometry is much easier to fabricate. The source set used is listed in Table XII, and count rate data measured with a plastic scintillator rod for the ^{235}U cylinder set are shown in Fig. 25. The slope of the

curve drawn through the points in Fig. 25 is 0.678, which indicates the gamma-ray signal is proportional to $(\text{mass})^{0.678}$. This exponent agrees with the $2/3$ power mass dependence expected for a surface area source. Thus the self-absorption is very important in ^{235}U . Further evidence is shown in Fig. 25 by the points plotted for other source geometries used for the doorway monitor evaluations. Such extended sources produce a signal as much as a factor of 9 larger than would be expected for a reasonably compact source geometry.

In the case of ^{239}Pu there is an additional consideration, because β decay of ^{241}Pu produces ^{241}Am , which decays with emission of a 60-keV photon. The ^{241}Am activity becomes the predominant feature of the ^{239}Pu gamma spectrum with time. The gamma activity for ^{239}Pu as a function of age is primarily the sum of the curves shown in Fig. 26. Any comparison of our ^{239}Pu sensitivity measurement would have to consider the efficiency of the unit at 60 keV and the age of the ^{239}Pu sample.

Other factors to be considered are the variable parameters in the logic module and electronics package. The two important ones are the $n\sigma$ detection level and the SCA windows. The $n\sigma$ level was set at $n = 4$ for both doorways; $n = 5$ was used for one set of measurements only on the NaI doorway. The SCA windows were set differently for ^{235}U and ^{239}Pu to define the optimum energy range for each. The energy range determined for each material is shown in Table XIII; the energies given for the plastic detectors are approximate because of the limited resolution of the detector. The corresponding background count rates and dose rate are given for scaling to different radiation background levels. If both ^{239}Pu and ^{235}U were to be detected simultaneously at the same station, a compromise

TABLE XI
MINIMUM SURFACE AREA CYLINDERS ISOTOPIC ANALYSIS
(ATOM %)

Sample	MASS NUMBER								
	234	235	236	237	238	239	240	241	242
^{235}U	0.998	93.26	0.421	---	5.32	---	---	---	---
^{238}U	0.0006	0.202	0.0032	---	99.79	---	---	---	---
$^{239}\text{Pu}^a$	---	---	---	---	0.012	93.81	5.81	0.349	0.022

^a ^{241}Am : 27 ppm on 8/22/73.

TABLE XII

HEIGHT = DIAMETER CYLINDRICAL SAMPLES

Nominal Mass (g)	^{235}U		^{238}U		^{239}Pu	
	Nominal Diameter (mm)	Finished Mass (g)	Nominal Diameter (mm)	Finished Mass (g)	Nominal Diameter (mm)	Finished Mass (g)
0.1	---	---	---	---	2.00	0.0998
0.3	---	---	---	---	2.88	0.2840
1.0	4.07	0.9794	4.07	1.000	4.31	0.9176
3.0	5.86	2.469	5.86	3.020	6.21	2.938
10.0	8.76	9.870	8.76	9.981	9.28	9.820
30.0	12.63	29.486	12.63	30.019	13.39	29.745
100.0	18.87	98.593	18.87	100.180	20.00	98.933
300.0	27.22	295.048	27.22	300.554	---	---
1000.0	40.65	987.153	40.65	1002.622	---	---

window would have to be used. We have not investigated this in detail, but the window would probably turn out to be 0 to 450 keV for both isotopes, or a 50- to 220-SCA window for ^{235}U with the LLD output of 50 to ∞ being used in the second channel for ^{239}Pu .

The usual procedure to determine the detection efficiency for a particular source was to walk through the doorway 20 times with the source in each of the

positions mentioned for a total of 80 passes. Bare source means the source was encapsulated with a minimum amount of plastic material, except for plutonium, which was encapsulated in 0.025-mm stainless steel. Background during testing was about 25 $\mu\text{R/h}$. The results are shown in Tables XIV, XV, and XVI.

Fig. 25.

Count rate vs mass for the ^{235}U cylinder sample set. Slope of the straight line is 0.678 indicating a $(\text{mass})^{0.678}$ dependence of the count rate.

Fig. 26.

Gamma activity of ^{239}Pu as a function of age. The source activity is the sum of two curves, and the ^{241}Am component becomes the dominant feature after a few weeks.

TABLE XIII
ENERGY WINDOWS USED FOR
DOORWAY TEST

Material	Doorway Energy Window ^a (keV)	
	NaI	Plastic
²³⁵ U	70-220 (1250) ^b	85-230 (2200) ^b
²³⁹ Pu	0-450 (1900) ^b	85-365 (2800) ^b

^aThe energy windows shown for plastic are incident photon energy intervals approximate to about ± 30 keV. The NaI window width uncertainty is about ± 5 keV.

^bBackground count rate (s^{-1}), in indicated window. These rates correspond to a natural background of about 25 $\mu R/h$.

Inconsistencies in these tables arise from the limited number of trials used, differences in walking speed between the individuals, differences in the exact source placement, differences in the height and weight of the individuals, which change body shielding, etc. But these data illustrate the "real life" usage of the portal monitor and are *not* values calculated from static measurements.

Table XIV is intended to point out further the difference in the way the sensitivity varies spatially in the two doorways. This table lists the detection probability for both doorways at a 4σ detection level for a number of sources. The minimum sensitivity area of the plastic doorway is its vertical center line, particularly at the top and bottom. This weakness is apparent in the first two columns of the table. For the NaI doorway the weak points are horizontal planes at

waist height, at the top, and, to a small extent, at the bottom, as is apparent from the results in Table XIV.

For comparison between doorways, the detection efficiency for the four test positions are averaged. These results are shown in Table XV. The sensitivities of the two doorways at 4σ are so similar that one is not preferred over the other. From the measurements, we would like to determine the mass of material that we can detect 50% of the time. The averaging between positions prevents us from analytically determining the 50% source; we can only estimate. These estimates are shown in Table XVI, where the mass for detection at 50% confidence is shown for the range of sources tested. The false alarm rate of 3 per h corresponds to the use of two channels, i.e., ²³⁵U and ²³⁸U simultaneously. For plutonium detection only one channel is used.

Table XVI emphasizes the expected degradation in performance of the doorway monitor for shielded, highly-enriched uranium. Whereas 1 kg of uranium shielded with 3.2-mm Pb is probably readily detectable by nonnuclear sensors, 10 or 100 g can undoubtedly be slipped through with very modest shielding. The situation is, of course, much better for plutonium because of the higher intensity and higher energy gamma activity.

C. Environmental Testing

The design for the portal portion of the doorway system anticipated both indoor and outdoor usage without auxiliary heating or cooling. No specific restrictions on outdoor environmental extremes were believed to be inherent in the construction, except that the NaI scintillators were not to exceed a temperature rate of change of about 5°C per hour.

A winter test was carried out with both doorways to determine the response to the extreme temperature

TABLE XIV
SPATIAL VARIATION OF DETECTOR PROBABILITY FOR SEVERAL SOURCES

Cylindrical Source	Detection Probability in Position Shown for Doorway at 4σ							
	Plastic Doorway				NaI Doorway			
	Head	Shoe	Pants Pocket	Shirt Pocket	Head	Shoe	Pants Pocket	Shirt Pocket
9.870-g ²³⁵ U Bare	0.90	0.50	0.95	0.95	0.90	0.80	0.95	0.95
2.469-g ²³⁵ U Bare	0.10	0.10	0.20	0.10	0.00	0.33	0.08	0.50
0.0998-g ²³⁹ Pu Bare	0.10	0.15	0.60	0.60	0.25	0.50	0.60	0.80
2.938-g ²³⁹ Pu in 3.175-mm Pb shield	0.95	0.55	0.95	0.95	0.80	0.80	0.95	0.75

TABLE XV

COMPARISON OF DETECTION PROBABILITIES FOR THE TWO DOORWAYS

Source (g)	Pb Shielding Thickness (mm)	Doorway Detection Probabilities		
		Plastic (4σ)	NaI (4σ)	NaI (5σ)
²³⁵ U cylinders	none			
2.469		0.10	0.20	0.10
4.6 ^a		0.70	0.70	0.35
9.870		0.85	0.90	0.75
²³⁵ U foil	none			
1 (0.025-mm-thick)		0.95	0.75	0.85
1.9 (0.51-mm-thick)		0.80	0.80	0.50
²³⁵ U shavings	none			
0.5		0.40	0.45	0.15
1		0.70	0.90	0.80
²³⁵ U cylinders				
295	1.6	0.65	0.80	0.20
987	3.2	0.80	0.70	0.40
²³⁸ U				
300	none	0.85	0.90	0.40
1002	1.6	0.95	0.95	0.50
1002	6.4	0.95	0.90	0.10
²³⁹ Pu				
0.1	none	0.35	0.50	0.20
0.284	none	0.95		0.95
0.918	1.6	0.70	0.60	0.03
2.94	3.2	0.85	0.80	0.45
9.82	6.4	0.95	0.60	0.25

^aA 0.9794-g and 2.469-g cylinder together give a signal equivalent to a 4.6-g cylinder using $S \propto m^{0.68}$.

fluctuation for this geographical area. A location was chosen where the doorways would receive the afternoon sun and cooling would be rapid at sunset. The results of temperature measurements show that the insulation provided by the styrofoam enclosure reduces the rate of change of temperature to about 2/3 of the ambient rate, if the change is at a moderate rate. However, on the first day, the observed temperature drop was about 15°C/h at sunset.

The NaI crystals cooled at about 10°C/h, therefore the restrictions on crystal cooling were not met for this extreme condition. One NaI scintillator crystal fractured and two others showed reduced pulse height resolution, which may indicate fractures. The location of the NaI crystals in the styrofoam insulation, with very little insulation around one corner, probably contributed to the temperature shock.

TABLE XVI

PORTAL MONITOR
DETECTABLE MASS^a

Sample (g)	Shielding (mm Pb)
93.5% ²³⁵ U	
4 (cylinder)	Bare
1.9 (0.51-mm-thick foil)	Bare
1.0 (0.025-mm-thick foil)	Bare
0.7 (shavings)	Bare
300 (cylinder)	1.6
1000 (cylinder)	3.2
99.8% ²³⁸ U cylinders	
~ 200	Bare
500	1.6
1000	6.4
94% ²³⁹ Pu cylinders ("fresh") ^b	
0.1	Bare
1	1.6
3	3.2
...	6.4
50	12.7

^aInternal false alarm rate $\approx$ 3/h.Detection confidence level $\geq$ 50%.^bInternal false alarm rate $\approx$ 1.5/h.

No further changes were observed during the test. All stress was apparently relieved on the first night. The effect of the fracturing on operation of the NaI doorway was negligible. The SCA window had to be widened slightly to accommodate the reduced resolution, but apparently no count rate loss resulted. The observed rms gain drift was 3% for the NaI and 6% for the plastic. Such changes are easily accommodated in the SCA windows used.

With the exception of the small drift, no adverse effects were observed for the plastic scintillator portal. The present structural design is adequate for the plastic scintillator for all reasonable environments. The results of these tests indicate that the NaI system should probably be used indoors only, although the overall system performance was not degraded during the environmental test.

D. Field Test Experience

Several field tests were carried out at local sites to determine what problems would be encountered in installing and using the doorways, and to ascertain what the false alarm rate would be in actual use. The sites chosen included plutonium and uranium fabrication areas where radioactive material was handled nearby and where the background was variable. Additional locations were chosen where radioactive sources were rare or distant and background fluctuations were smaller. While some of the sites chosen did have attendant security personnel, the operation of the doorway monitor was usually unattended. Information gained in the test was derived from auxiliary instrumentation, such as scalars or chart recorders for counting alarms and traffic, and from the photographic record made by the system camera. On several days the operation was monitored visually by an individual involved in the development of the system, and information useful in interpreting the instrumentation records was obtained.

1. **Installation Requirements.** Several minor problems, which constrained the placement of the doorway, were encountered during these tests. A security inspector's radio transmitter with an indoor antenna caused some interference with the operation of the system. Relocating the antenna, in this case, would have provided a simple solution. Another limiting factor was the field-of-view of the camera. The camera must be positioned 4.5 m in front of the doorway exit to allow a 1.2-m by 1.8-m field-of-view to photograph both the clock and the individual. The doorway therefore must be located where no doors or other structures intervene within 4.5 m of the exit. If enough room is not available the camera optics could be changed or not using the camera at all could also be a logical choice for the attended station. The width of these prototype doorways also limited their positioning. Some carts and hand trucks commonly used at the specific sites would not fit through the 0.76-m-wide portal. This problem could be eliminated by specifying portal dimensions for each installation or by limiting cart sizes. Changing the dimensions of the portal monitor would obviously affect its sensitivity.

2. **False Alarms.** Several circumstances were encountered that resulted in false alarms that were non-statistical in nature. The first is the problem of a sudden rapid increase in background causing the alarm level to be exceeded. The logic circuit then

alarms until an updated background is obtained. This requires at least 35 s for our present logic parameter settings. The update period will be considerably lengthened if traffic is present at the same time, because the traffic would cause occupied alarms that inhibit the background update.

A second, similar situation will occur when a dense queue forms in the portal. Bodies in the doorway partially shield the detectors and reduce the background count rate. When the queue disperses, a lower background has been stored and the return to normal background causes alarms until the background is again updated to the normal level. We observed the queuing effect only at an exchange badge station, where a lengthy wait was required. At stations where only a badge check is required, the traffic flow is adequate so that the effect does not occur.

The third type of false alarm encountered with the first generation logic occurred during passage of very large radioactive sources. As noted earlier, the high count rate generated by such passage causes accumulator overflow and continuing alarms until the logic is manually reset. This problem will not occur with the second generation system, which does not use an accumulator.

The last source of false alarms noted during testing was a vacuum cleaner. On several occasions pictures of the janitor vacuuming the portal were obtained. Increasing the warning level to 5σ seemed to eliminate this problem.

All but the third false alarm situation listed are self-remedying; but with the prototypes as presently set, the time for normal operation to resume could be as much as 90 s. During this period the traffic flow would have to be stopped or the doorway located to minimize changing backgrounds and queuing.

3. Film Results. An example of the film record made during an alarm is shown in Fig. 27. Generally, an individual is recognizable and the wall clock is readable when a typical, inexpensive movie editor is used to view the film. However, the magnification is inadequate for reading the digital calendar-clock originally used in the doorway, which requires a magnification of 7 for the 1.58-cm-sized numerals. If a numeral height of 2.25 cm could be obtained, they would be readable on the editor.

The normal inside hallway lighting was adequate for the black and white MFX or MFA film used. Film readability was also good when daylight was the primary source, although the image quality deteriorates when back-lighting occurs. Reduced lighting at night would make a separate doorway light source necessary for a 24-h operation. Camera

operation was good during the prototype tests; only two film rolls failed to give good results. In one case, an operator error, the cartridge drive was not engaged. In the other, the film failed to properly wind through, although the film indicator moved. Color film gave poor results for indoor operation with existing light. The main fault was lack of the extreme latitude required for typical indoor operation.

Examination of the film record of the field tests provided verification of the alarm and traffic data recorded on scalars. Whenever agreement was not found, the film record was correct, and the total alarm rate could be determined from the film. Whenever traffic was light, the occupied alarm rate could also be estimated from the film record.

The film record was also used to look for individuals who habitually carried radioactive sources that might cause alarms. We anticipated that radium dial watches and medical radioisotopes would be likely sources. The film record was examined and prints were made of the film frames showing individuals who occupied the doorway at the time of an alarm. The record of such individuals is incomplete since identification is difficult or impossible if another person screens the individual from the camera's field-of-view or if the individual's travel is away from the camera. However, any source capable of alarming 50% of the time and carried by an individual passing the portal daily would be expected to produce several identifiable photographs during the 6- to 8-wk test period. Two individuals did appear twice and one individual appeared often. The latter carried residual activity from a medical diagnostic procedure, whereas the other two are the only evidence for other lower activity sources.

4. Alarm Rate Results. Results derived from field test data are shown in Table XVII. The first two columns display the location and detector type used. In the third and fourth columns the warning level and expected statistical false alarm rate for the given warning level and number of channels used is tabulated. These rates have been discussed previously in Sec. VII.B. The traffic rate in the fifth column is tabulated from the number of times the light link was broken. The total observed alarm rate in column six includes both occupied and unoccupied alarms. These alarms arise mainly from the statistical rate (expected value tabulated in column 4), background changes, and the movement of sources nearby. The last of these three contributions dominates the observed rates in the locations where radioactive material was frequently moved nearby (plutonium facility and uranium facility near SNM). For these two areas the total observed alarm rates (column 6)

Fig. 27.
An example of the film record made during an alarm.

TABLE XVII
FIELD TEST RESULTS

Location	Doorway Type	Warning Level	Statistical Alarm ^a Rate for Number of Channels and Warning Level Used (per h)	Traffic Rate ^a Observed (per h)	Total Alarm ^a Rate Observed (per h)	Occupied Alarm ^a Rate Observed (per h)	Occupied Alarm ^a Rate Calculated from Observed Total Alarm Rate and Traffic
Plutonium facility	Plastic	4σ	1.6	71	13.9	0.69	0.27
Uranium facility (near SNM)	NaI	4σ	3.1	not measured	15.1	0.31	not measured
Uranium facility (away from SNM)	NaI	4σ	3.1	23	3.46	0.10	0.02
Administration area	Plastic	4σ	3.1	105	6.30	0.54	0.18
Administration area	Plastic	5σ	0.03	105	3.34	0.35	0.10

^aThe indicated rate is calculated for a 24-h period. Traffic was actually present for a period of about 11 h per day.

are 5 to 10 times those expected from statistical background fluctuations alone (column 4). When the portal monitor was moved away from SNM at the uranium facility, the total observed alarm rate dropped to essentially that expected from statistical fluctuations.

The observed total alarm rates at the administration area showed equal contributions from the expected statistical rate and the other contributions mentioned above. The 4 σ and 5 σ data are consistent. The administration area could be expected to have a lower total alarm rate than was observed. However, experimental areas including an accelerator are nearby; the electrical wiring is poor and power interruptions were observed; and the individual with the residual medical isotope had daily business in this area. These probably account for the increased alarm rate observed in this area.

The total observed alarm rates (column 6) just discussed should not cause over concern. The security personnel at the portal are alerted with an audio and visual alarm only when an alarm occurs and the doorway is simultaneously occupied. If the doorway is not occupied, then the alarm is a "silent" alarm because the only action initiated is a photographic record of the unoccupied doorway. Thus the occupied alarm rates (column 7) are the average rates at which the guard is alerted with the portal monitor alarm. Whereas this rate will be proportional to the total alarm rate (column 6) and the traffic rate (column 5), the coincidence requirement reduces the important occupied alarm rate by factors ranging from 10 to 50 for these data. These rates average from less than one to four or five occupied alarms per 8-h period. These rates do not seem excessive except that they are average values and one would expect that the most likely time for occurrence would be when traffic flow is greatest. The film records verify this. They frequently show one or more occupied alarms during the brief, but high, morning traffic rush.

As noted in Table XVII, these values are averages for a 24-h period even though significant traffic was present for only about half that time. This has little effect on total observed rates when they arise from statistical fluctuations only (i.e., uranium facility away from SNM), because these alarms are statistically distributed throughout the entire 24-h period. However, for an area where most of the alarms are caused by movement of SNM nearby (for example, plutonium and uranium facilities near SNM) most of the alarms occur during the portion of the day that traffic is present. The occupied alarm rates during these periods may be approximately 2 to 4 times greater than the listed values in column 7.

The calculated occupied alarm rate in column 8 is obtained from the product of the total alarm rate and the fraction of time the doorway is occupied. The latter factor is obtained from the traffic rate and an assumed 1-s occupancy time. The uncertainty discussed above also applies here. Comparing columns 8 and 7, the observed rates are always higher than the calculated rate. The difference can be attributed to actual source traffic. Alarms caused by radium watches, medical radioisotope treatments, and other radioactive source traffic apparently are as big or bigger a problem than statistical alarms.

In all cases the occupied alarm rates are much higher than those from statistical effects only and are also very dependent upon the particular portal location. One must not rely excessively on other experience or calculated rates. On-the-spot experience is necessary to ensure accurate consideration of all false alarm sources.

IX. PORTAL MONITOR COSTS

Stricter AEC regulations governing the protection of SNM and nuclear industry's increasing awareness of the need for additional security measures have increased the interest in this monitoring system. For facilities that have to install multiple units, cost becomes an increasingly important factor. Expense played an important role in the design of this system, and effort was made to keep costs down.

Table XVIII shows estimates of the cost of the portal monitors described in this report using a second generation logic system. Labor has been included as shown, but no profit is included in these figures. The labor costs on these prototypes are higher than they would be on production versions of the same design. The fabrication cost of the logic module is intermediate between that for a production line (lower) and that for assembly of a first prototype unit (higher). No figures have been included for the one-time cost of making printed circuit board masters.

After completion of these two prototypes with the first generation logic, we submitted design drawings of the complete system to about 20 commercial vendors who might have an interest in manufacturing this instrumentation. Six vendors submitted bids on the system, but funds did not become available to purchase any of our units from a commercial vendor. However, the lowest bids were consistent with our price estimates, considering that a profit has not been included in the Table XVIII values. Systems like these could possibly be purchased commercially for under \$10 000.

TABLE XVIII
PORTAL MONITOR COST ESTIMATES
(LABOR AT \$15/h)

		<u>NaI</u>	<u>Plastic</u>
I.	Door Frame/Detector Assembly		
	A. Foam Frame Assembly		
	1. Material	\$ 50	
	2. Fabrication	500	
		\$ 550	\$ 550
	B. Detector Units		
	1. NaI/Pb shielding/PMTs/ voltage dividers	2600	
	2. Plastic/Pb shielding/PMTs/ voltage dividers		1465
	C. Electronics		
	1. Preamps ORTEC 113 w/long power cable (2)	246	
	2. Clock calendar	40	
	3. Light link		
	a. Material	20	
	b. Fabrication	60	
	4. High voltage distribution		
	a. Material	8	
	b. Fabrication	15	
	5. Low voltage distribution and cabling		
	a. Material	50	
	b. Fabrication	130	
		569	569
II.	Instrumentation		
	A. NIM Bin ORTEC 401A/402A	575	
	B. High Voltage Supply Power Designs AEC 315B	390	
	C. Amplifier ORTEC 435	235	
	D. SCA ORTEC 406A	250	
	E. LASL Logic Module (second generation)		
	1. Material	610	
	2. Fabrication	660	
	F. Alarm		
	1. Material	20	
	2. Fabrication	15	
		2755	2755
III.	Surveillance Camera		
	A. Material	160	
	B. Modification Cost	15	
		175	175
		<u>\$6649</u>	<u>\$5514</u>

X. CONCLUSIONS

It is possible to build a relatively inexpensive portal monitor that can be used at nuclear facilities to help deter the diversion of special nuclear materials by way of monitored exits. These monitors, of course, provide only one component of an effective diversion safeguards system. However, the combination of radiation detectors and digital logic explored in this study seem optimum for the purpose.

Clearly this particular type of instrumentation can be defeated by a knowledgeable adversary at a level of diversion that is perhaps 10 to 100 g of plutonium per pass and 100 to 1000 g of highly-enriched uranium per pass. From the basic physics of nuclear material, obviously even a drastic increase in expenditure for radiation detectors and a relaxation of the self-imposed constraints on cost and simplicity will not materially alter this situation. We therefore have concluded that radiation surveillance of portals at the level represented by the instrumentation in this report is reasonable and proper but that additional assurance should be obtained by other means.

These studies have also demonstrated the necessity for carefully stating acceptable performance standards for equipment of this type. As of December 1973, we concluded that existing AEC guidelines were inadequate in some details. Critical parameters including SNM sample specifications and detection and false alarm probabilities were therefore documented for the AEC.

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