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Edited by Dorothy C. Amsden, Group Q-2
Composition by Belinda K. Haag, Group Q-2
Illustrations by A. Gayle Smith and Randall Busch, Group Q-2

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Vehicle Monitors for Domestic Perimeter Safeguards

P. E. Fehlau
C. Garcia, Jr.
R. A. Payne
E. R. Shunk

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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VEHICLE MONITORS FOR DOMESTIC PERIMETER SAFEGUARDS

by

P. E. Fehlau, C. Garcia, Jr.,
R. A. Payne, and E. R. Shunk

ABSTRACT

This report compares several types of special nuclear material monitors used to search motor vehicles at area exit gates. These monitors use either portable, hand-held instruments or stationary radiation detection instruments. Stationary monitors have a detector portal or a detector array located in the roadbed at a vehicle exit. Static measurements and operational evaluation provide a performance comparison of three types of monitors: hand-held instruments, vehicle portals, and a high-sensitivity roadbed monitor. Still higher sensitivity is possible by placing detectors overhead as well as in the roadbed; such a combined monitor does not yet exist, but the report estimates its performance. The cost for a combined monitor increases significantly when both a canopy and a roadbed detector pit are constructed; however, the performance of the combined monitor exceeds that obtained with other monitor configurations.

I. INTRODUCTION

A. Vehicle Radiation Monitoring

Motor vehicles are monitored at the exits to all special nuclear material (SNM) access areas and some protected areas to comply with DOE regulations[1] that personnel, packages, and vehicles be searched for plutonium and enriched uranium. At present, vehicles are searched for SNM either by radiation detectors located beside an exit gate in a fence (gateside monitor)[2] or, most often, by hand-held instruments[3] in a manual search to detect radiation.

The work summarized in this report resulted from a request by the DOE Office of Safeguards and Security that the Los Alamos Advanced Nuclear Technology Group investigate the effectiveness of vehicle monitoring. In response to the DOE request, the group decided to construct an optimum monitor, using static measurements and operational evaluation to compare its performance with that of conventional monitors. The monitor that we constructed is a roadbed monitor[4] with neutron and gamma-ray detectors in pits beneath a vehicle monitoring point. By locating the detectors in pits, we achieve the minimum separation between the radiation detectors and the cargo in medium-size vehicles.

From our investigation, we conclude that modest sensitivity for monitoring medium-size vehicles can be obtained with a relatively inexpensive monitor, which we call a vehicle portal, provided that appropriate detectors, detector position, and monitoring logic are used. The roadbed monitor offers still better performance, particularly if overhead detectors are added to improve monitoring of tall vehicles. However, construction of both a detector pit and a canopy to support the overhead detectors is expensive. We recommend the roadbed monitor without overhead detectors for situations where minimum obstruction is important; the roadbed monitor with overhead detectors is better for situations where maximum performance is required.

B. History of Vehicle Monitoring

Vehicle monitoring began about 1974 at the DOE Rocky Flats Plant, which developed a vehicle SNM monitor[2] for plutonium. The monitor had fixed gateside detectors that replaced hand-held survey meters for vehicle searches. The Rocky Flats prototype gateside monitor consisted of small thallium-activated sodium iodide [NaI(Tℓ)] detectors attached to gate posts, a vehicle presence detector, and an electronics and logic unit adapted from personnel monitor electronics used at the plant.[5] Since then, other DOE facilities have used an itemized specification for the Rocky Flats gateside monitor to purchase their own vehicle monitors. Tom Scurry Associates* is one manufacturer that offers a gateside monitor, based on the Rocky Flats design, as a catalog item. A similar gateside monitor is now available commercially from National Nuclear Corporation** (Fig. 1). A hand-held instrument with detection logic (Fig. 2) was designed in 1974 at Los Alamos[3] for SNM monitoring of personnel, packages, and vehicles. It has found widespread use at DOE facilities because it is inexpensive and can be used by security inspectors after a short training period. The Los Alamos hand-held monitor, now commercially available from National Nuclear (Model HM-3) and from CMS, Inc.† in a slightly different design (Delta Rate Monitor), is a lightweight, battery-powered package containing a NaI(Tℓ) gamma-ray-scintillation detector, signal-conditioning electronics, and alarm-logic circuitry.

A new approach to vehicle monitoring that places detectors closer to the vehicle by positioning them under it resulted in the roadbed monitor (Fig. 3), developed at Los Alamos in 1978. The monitor was constructed at the exit gate to Pajarito†† Site, where the Advanced Nuclear Technology

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*Boulder, Colorado.
**Mountain View, California.
†Goleta, California.
††Pronounced pä-hä-rē-tō; Spanish for little bird.

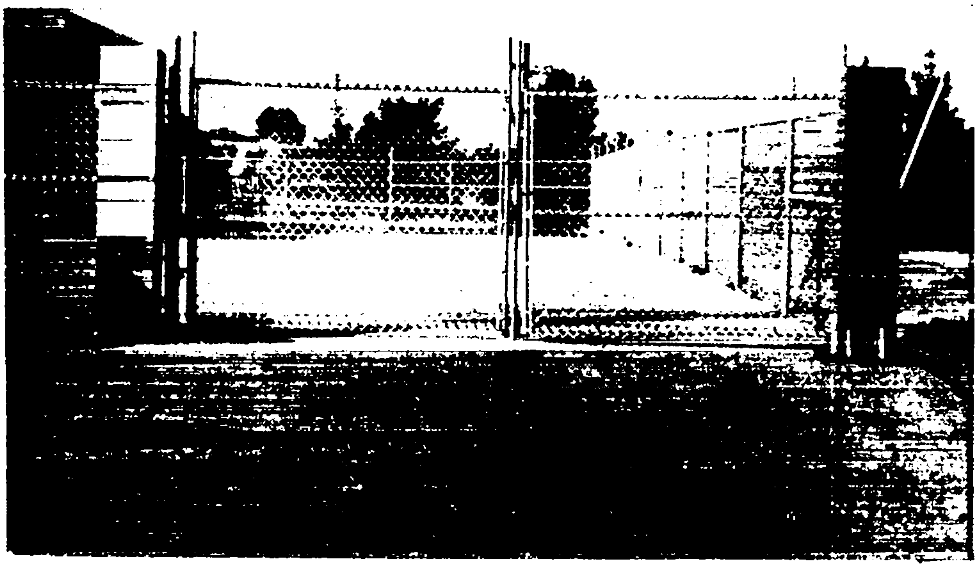

Fig. 1.
Typical gateside monitors use radiation detectors to monitor a vehicle as it leaves a protected area. A better location for the detectors is well inside the exit gate, on either side of a vehicle as it approaches or waits for clearance to depart.

Group is located. Because all of its detectors are located beneath the vehicle, the roadbed monitor constitutes a one-sided monitor with reduced sensitivity for monitoring tall vehicles. A canopy to support overhead detectors would correct this deficiency, but has not been constructed. In Sec. VI we estimate what the monitor's sensitivity would be with overhead detectors for comparison with other two-sided monitors. We plan to construct a canopy in the future and to verify the predicted performance.

In 1981 we began evaluating a prototype vehicle portal (Fig. 4). The portal differs from the earlier gateside monitors by incorporating large, solid, organic (plastic) scintillators; such scintillators are most appropriate for detecting shielded SNM. The vehicle portal is positioned well inside the protected area and monitors vehicles traveling at low speed. The portal monitor's sensitivity is somewhat lower than that of the roadbed monitor because the presence of a vehicle causes a large reduction in the monitor's background. Thus, a larger signal is needed for detection. At present, portal monitors are applied to monitoring situations where intense signals from nuclear material must be detected, as is the case for plutonium monitoring and entry control stations at nuclear weapons storage facilities.

Fig. 2.
The use of hand-held monitors to detect SNM requires that an inspector enter the vehicle wherever possible to conduct a thorough search. The thoroughness of the search strongly influences the sensitivity of hand monitoring.

C. Vehicle Monitoring Difficulties

No matter which monitor is used, it is difficult to monitor vehicles with radiation detectors because vehicles are large, requiring the detectors to be distant from the vehicle interior where SNM may be hidden. Moreover, shielding of the SNM radiation may result from the vehicle structure and from additional shielding materials carried by the vehicle. To overcome the signal reduction caused by distance and shielding, the best solution is to optimize detector performance wherever possible by

(a) selecting the most effective detectors--large plastic scintillators;

(b) placing them where they will be most effective--below and above the vehicle;

Fig. 3.
The roadbed monitor at Pajarito Site searches a Ford 1-ton van from below while the occupants present their badges to the inspector for exit clearance. The monitor consists of gamma-ray and neutron detectors in pits covered with aluminum grating and aluminum diamond plate.

(c) allowing a reasonably long period of monitoring time; and

(d) compensating for vehicle-caused background depression by using the monitor's logic program to lower the alarm level when the monitor is occupied.

In the following sections, we will describe the important considerations in vehicle monitor design—monitor operating principles, radiation background, and SNM signatures—before we present our evaluations.

II. SNM MONITOR FUNDAMENTALS

A. Detecting SNM

SNM monitors detect the presence of SNM by sensing its radiation. Both gamma rays and neutrons are emitted by SNM, but gamma rays are generally more significant; the neutron emission rate for uranium materials is often too low to be observed. SNM monitors determine when radiation from SNM is present by comparing a measured gamma-ray intensity, when the monitor is occupied, to an expected intensity, which is calculated from background radiation levels that were measured before occupancy.

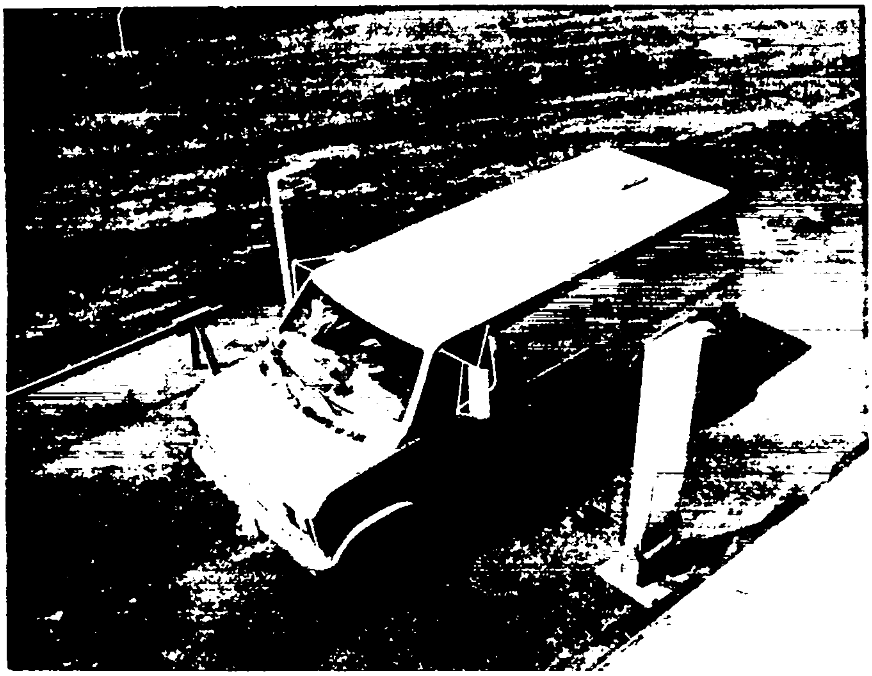

Fig. 4.
This prototype vehicle portal, built with large plastic scintillators, monitors vehicles as they pass through it.

B. Alarm Levels

The background radiation sensed by a monitor includes natural gamma rays from the monitor's surroundings and, possibly, radiation from work area activities. The additional radiation from SNM located in a vehicle can cause the total radiation intensity to exceed a limit or alarm level determined by adding an increment to a previous average background. Figure 5 simulates a monitor's background and the alarm level it uses. The size of the added increment that is used to calculate the alarm level not only establishes the monitor sensitivity, but also determines the probability of a false alarm occurring from statistical variation in the monitoring measurement. In general, the increment represents the amount of radiation from SNM needed to cause an alarm, although the amount of background suppressed by the presence of a vehicle is also important. Figure 6 illustrates the background suppression that takes place in vehicle portals and that seriously diminishes their sensitivity.

The example in Fig. 6 uses a common alarm increment, a multiple of the square root of the background $B^{0.5}$, which is the standard deviation of the average background. Thus, the alarm level A is, for example, $A = B + 4B^{0.5}$, where B is the average background. This choice for the alarm increment makes the false-alarm rate in an unoccupied monitor constant when the average background varies, although the detection sensitivity will change. Another possible choice for the increment is a constant about equal to an anticipated value of $4B^{0.5}$. This choice maintains detection sensitivity while the false-alarm rate changes with background variation.

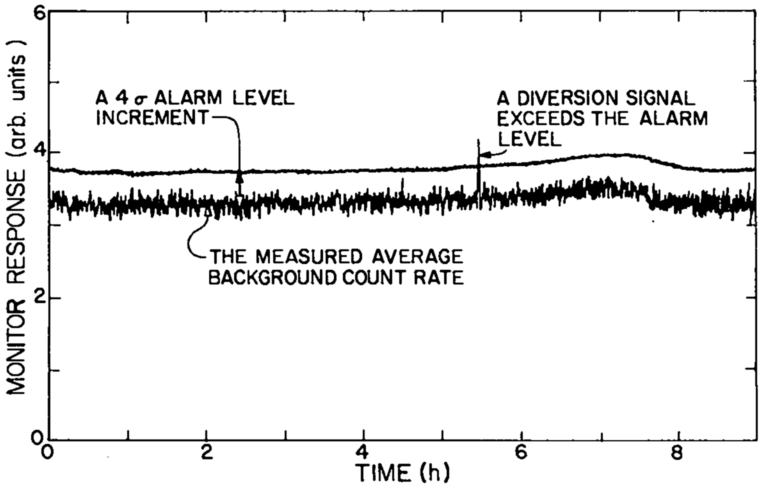

Fig. 5.
This strip chart tracing simulates the background count rate detected by a vehicle monitor. The monitor's logic electronics measures an average value for the background count rate that lies near the center of the broad trace. When an alarm-level increment is added to the average background, the upper narrow trace results. An increase in count rate appears at about 5 h 30 min on the strip chart from radioactive material passing nearby.

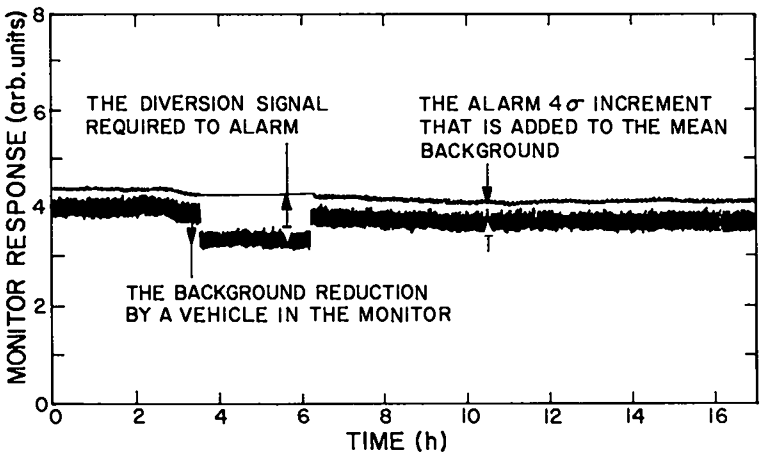

Fig. 6.
In a vehicle portal, a vehicle causes a dramatic reduction in detector background by coming between the detector and the environment in its field of view. As a result, a larger diversion signal is required for detection. This strip chart and the one in Fig. 5 use long-term records for illustration.

C. Detection Sensitivity

The amount of SNM source radiation that a monitor can detect is affected by the distance between the SNM and the detectors. In fixed vehicle monitors, that distance is much larger than it would be, for instance, in a walkthrough personnel SNM monitor. Typically, as the spacing between the large detectors of a walkthrough monitor increases, the number of detected source counts decreases about in proportion to the inverse separation of the detectors; but background, of course, remains the same. A figure of merit for detection of SNM is the signal-to-noise ratio, the ratio of the detected source counts to the standard deviation of the background (the noise), written as $S/B^{0.5}$. As the detected net signal S decreases with the separation needed to monitor vehicles, the figure of merit and the performance sharply decrease, compared to personnel monitoring. A similar effect takes place in manual searching of vehicles where scanning wide spaces often leads to a greater distance between the monitor and the objects being searched.

D. SNM Shielding

A second difficulty encountered in vehicle monitoring is the reduced intensity of SNM radiation by lead or other shielding materials. Not only is some shielding provided by a vehicle's structure, but vehicles are also capable of transporting quantities of shielding material that greatly attenuate source radiation without being observed in a casual visual inspection. Figure 7 shows the relative intensity of plutonium neutron and gamma radiation transmitted through lead and neutron shielding material, as measured with the roadbed monitor. Relatively thin lead layers cause large attenuation in gamma radiation whereas greater thicknesses of shielding are needed to reduce the neutron intensity. Techniques for detecting the shielding cannot be applied to vehicles—as, for example, in metal inspection devices for airport passengers—because vehicles are themselves metallic. Thus, we expect the effectiveness of vehicle monitoring, in general, to be lower than personnel monitoring, because of the effects of both detector spacing and shielding. Our goal is to obtain the best performance possible.

III. SNM RADIATION

A. Special Nuclear Material

The term <u>special nuclear material</u> is used in physical protection regulations[1] for plutonium and for uranium enriched in the isotope ^{235}U or ^{233}U. The properties of the uranium isotope ^{233}U and the plutonium heat source material ^{238}Pu make them more intense radiation emitters than the weapons materials containing mostly ^{235}U and ^{239}Pu. We are primarily concerned with detecting the latter, low-intensity materials. The fact that the other isotopes, ^{233}U and ^{238}Pu, emit similar but more intense and more penetrating radiation means that a monitor will detect them more easily than weapons material. Of the two low-intensity emitters, uranium is by far the lower intensity emitter, hence we concentrated on appraising its detection as a worst case material. In general, we have attempted to use the

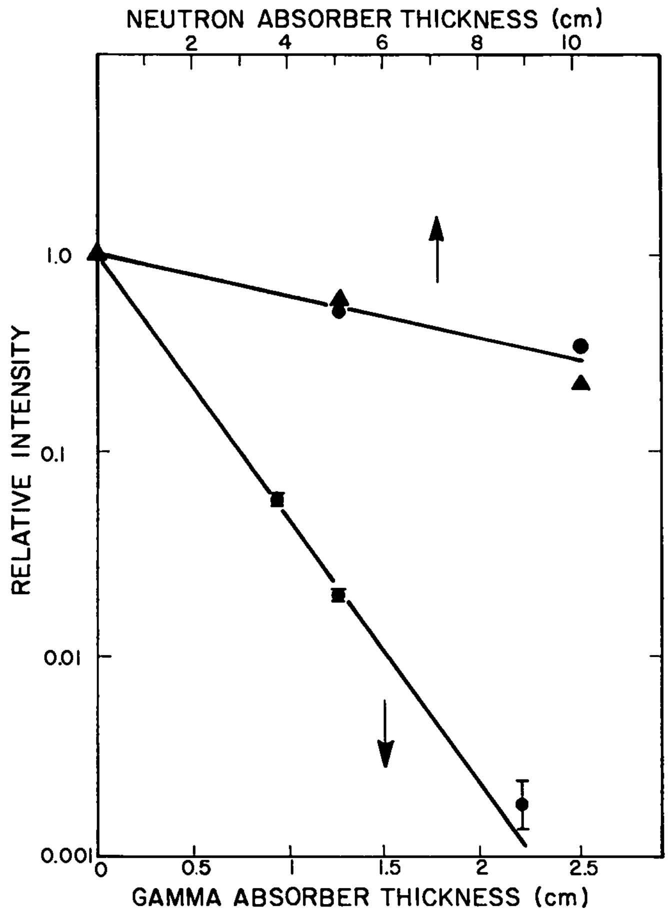

Fig. 7.
The relative amounts of gamma-ray and neutron radiation transmitted through common shielding materials are vastly different. The plutonium gamma rays are stopped in a few centimeters of lead, whereas plutonium neutrons are highly penetrating. Unfortunately, HEU emits few neutrons and we must rely on gamma-ray detection. The neutron shields were 5% boron polyethylene (▲) and 30% boron polyethylene (●), and the gamma-ray shield was lead (⧳).

configurations hardest to detect so that our results would apply to all other situations, not just to those where some particular feature permits detection.

B. Uranium

Uranium is enriched in the isotope ^{235}U from a few percent to 93% or more. Because the ^{235}U isotope is the most intense gamma-ray emitting isotope of uranium, a quantity of uranium is easier to detect as ^{235}U enrichment increases. The question of how a fixed mass of the isotope ^{235}U in different enrichments of uranium can be detected was answered by an analysis[6] that used a weighting factor proportional to the amount of material of that enrichment required to form a critical mass. When the weighting factor—important to a diverter intent on constructing a nuclear weapon—is included, the signal, weighted by criticality amount, is least for highly enriched material. Thus, by using highly enriched material to establish performance, other enrichments will also be detected, as well or better, relative to the criticality value.

The critical mass argument holds for bare SNM, but when shielding is added to the SNM most of the signal dependence on enrichment disappears, as Fig. 8 shows for measurements in one of the gateside monitors that we examined. Thus, with shielding, highly enriched uranium (HEU) remains a valid test material. The response for other monitors and different forms of uranium is similar; when weighted for criticality amount, lower enrichment material containing the required ^{235}U mass is easier to detect, and shielding does not change that conclusion. We used samples of HEU (93% ^{235}U) as a worst case test material in most of our comparisons. The specific composition of the samples that we used is given in Table I.

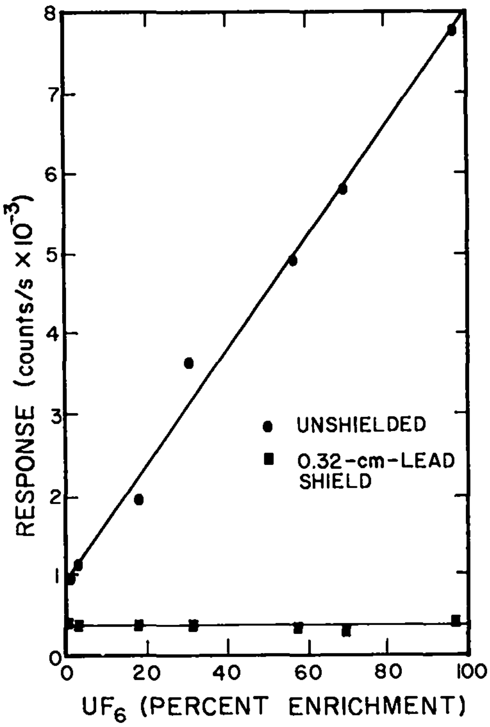

Fig. 8.
Thin lead shielding removes the ^{235}U radiation, but the remaining radioactive isotopes in this UF_6 contribute a fairly uniform radiation intensity as the enrichment changes.

C. SNM Self-Shielding

Another consideration for specifying monitor performance in terms of a detected quantity of SNM is that the material itself provides shielding for

TABLE I

ISOTOPIC COMPOSITION OF TEST MATERIALS

HEU		Weapons Grade Plutonium	
Isotope	Atom (%)	Isotope	Atom (%)
^{234}U	0.10	^{238}Pu	0.01
^{235}U	93.26	^{239}Pu	93.81
^{236}U	0.42	^{240}Pu	5.81
^{238}U	5.32	^{241}Pu	0.35
		^{242}Pu	0.02

its own gamma rays. A description of the radiation emitted by uranium and plutonium isotopes in our samples appears in Table II. The table lists a source layer depth from which most of the observed radiation escapes. The shallow depth of the escape layer causes the material to be a surface source of radiation and, therefore, source geometry is very important. The intensity of detected source radiation will depend on the size of the SNM, not on its mass. Figure 9 illustrates that extended thin or dispersed samples of HEU, such as foils or shavings, emit up to nine times as much radiation as a compact cylinder. These data are for ^{235}U radiation, but the result is the same for the radiation from ^{239}Pu. In our work we use compact samples (the lowest intensity samples because they have the minimum surface for their mass) to assure that we obtain adequate performance. Other physical and chemical forms of SNM are more easily detected. We made further use of the data shown in Fig. 9 to extrapolate from our measured results. The slope of the straight line is 0.67, typical of a surface source of radiation. Thus, for our compact geometry sources, we calculated mass detection limits from the measured response by the scaling rule

$$M = M_0\left(\frac{S}{S_0}\right)^{1.5} ,$$

where the subscript zero denotes measurement, M mass, and S signal count.

TABLE II

RADIATION PROPERTIES OF TEST MATERIAL ISOTOPES

Isotope	Energy Range (keV)	Specific Emission $(s \cdot g)^{-1}$	Approximate Source Layer Depth (mm)	Comments
^{235}U	75 - 210	6.18×10^4 gamma rays	1	Uranium K series x rays can double the listed intensity in thin samples
^{238}U	80 - 1001	129 gamma rays	≤ 21	Uranium K series x rays and bremsstrahlung from ^{234}Th daughter not included
^{239}Pu	80 - 770	3.33×10^5 gamma rays	1 - 6	Plutonium K series x rays not included
^{240}Pu	fission spectrum	900 neutrons		No appreciable self-absorption in small samples
^{241}Pu	59.6	4.6×10^{10} gamma rays	≤ 1	Intensity is per gram of the daughter, ^{241}Am; intensity is time variable, easily shielded

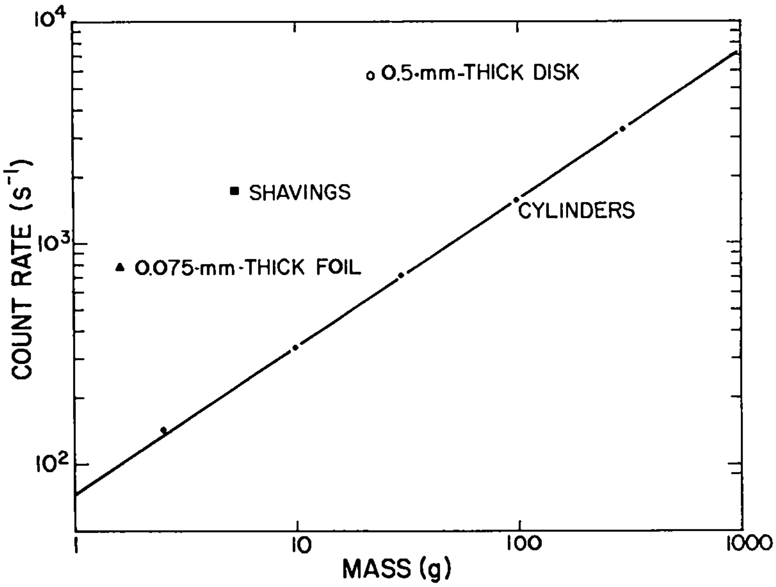

Fig. 9.
The surface area of a uranium sample is the chief factor in the amount of gamma-ray radiation emitted. The thin samples emit much more radiation for their mass than the uniform height-equal-to-diameter cylinders.

D. Plutonium Characteristics

Our discussion concentrates on uranium because it has a lower specific activity (number of emitted gamma rays per gram) and emits lower energy radiation than plutonium, which makes it the more difficult material to detect. However, all of the characteristics we discussed for uranium also hold for plutonium. Self-shielding is important for plutonium; when the material is dispersed, more of its intrinsic radiation escapes and it is easier to detect. In our experiments, we used metallic spheres or cylinders and a compact-geometry 25-g PuO_2 sample that was encapsulated in a height-equal-to-diameter cylindrical container completely filled by the sample. Another aspect in detecting plutonium involves the isotope ^{241}Pu that decays to a daughter with intense 60-keV gamma-ray activity. Although the ^{241}Am 60-keV radiation can be a great help in detecting the presence of plutonium, its intensity can vary with time. When ^{241}Am is chemically separated from plutonium--for example, in recently fabricated material--the isotope grows back at a slow rate (Fig. 10). Moreover, the soft 60-keV radiation is easily shielded by the metal components of vehicles. We used light cadmium shielding for our plutonium samples so that the results would apply to recently fabricated material; aged and unshielded material is easier to detect.

E. Energy Windows

The gamma-ray energy range for the materials in Table II differs in extent; each material has its own intensity pattern in its gamma-ray energy

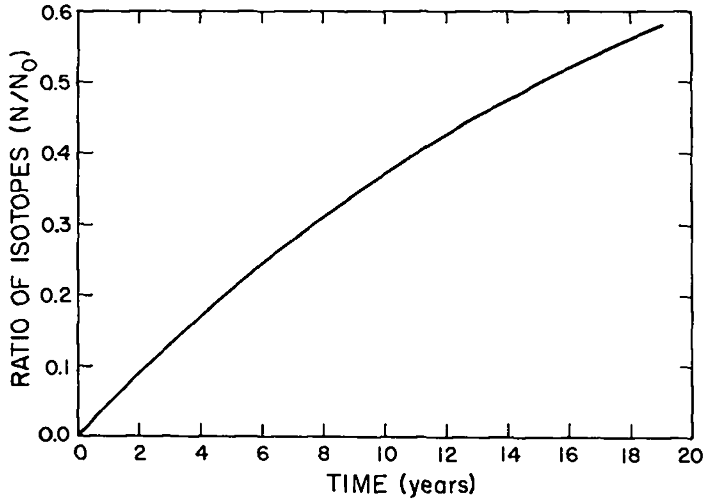

Fig. 10.
The prolific gamma-ray emitter ^{241}Am grows into chemically separated plutonium as its parent ^{241}Pu decays. This plot shows the ratio of the number of ^{241}Am nuclei N present as a fraction of the original number of its parent isotope, N_0.

spectrum. To obtain the best performance for a particular material, the SNM monitor must detect radiation in an appropriate gamma-ray-energy window. Optimum gamma-ray-energy windows have been discussed elsewhere for detecting bare SNM in personnel monitors[7] and for detecting bare and shielded plutonium with NaI(Tℓ) detectors.[8] After examining the data base for Ref. 8, we determined that the energy window from just above amplifier noise to 450 keV would be the best choice for detecting both bare and shielded plutonium.[4] Where heavily shielded uranium detection is needed, a wide window is appropriate. This wide window is provided by a lower-level discriminator set just above noise. These two cases, shielded plutonium and uranium detection, can be combined by means of separate logic channels (as in Ref. 7) or by a single logic channel and the wide uranium window. The second choice leads to slightly poorer but still acceptable performance for plutonium. Finally, when both shielded plutonium and unshielded uranium must be detected in a single energy window, the window extending from just above noise to 450 keV is again the best choice.

F. Neutrons

So far we have discussed gamma-ray characteristics of materials because metallic uranium emits only gamma rays in useful quantities. Plutonium contains neutron-emitting isotopes in large enough quantity that we can use its neutron emission for detecting diversion under some conditions. Gamma-ray emissions from unshielded plutonium are so intense that neutron detection is not a competetive technique for detecting diversion. However, when heavy shielding is present, as it can be in a motor vehicle, neutron monitoring looks like a good approach because it is relatively difficult to shield neutrons, as we saw in Fig. 7. Thus, a neutron monitor could be used when plutonium monitoring is the only requirement. (Remember that a neutron monitor will not detect metallic HEU.) Our plutonium test samples had about 6% ^{240}Pu content, which made them relatively weak neutron sources; thus, as with the gamma-ray sources, we are using a worst case test sample for neutron-emitting materials.

IV. DETECTORS AND THEIR PLACEMENT

A. Detector Location

Commercially available gateside monitors position NaI(Tℓ) detectors at the sides of a vehicle gate (Fig. 1). We believe this is poor positioning because monitoring takes place while the vehicle is actually departing. A better location for detectors is well inside the closed gate. Therefore, we decided to place the detectors on both sides of a vehicle as it approaches an exit gate. At that location, the vehicle portal detectors can be spaced one traffic lane apart, as in our prototype vehicle portal (Fig. 4).

Another configuration positions the detectors in the roadbed beneath the vehicle where they are closest to the vehicle and its contents. Initially, we planned to use our roadbed monitor as a laboratory test bed, but we were able to build the monitor at a security gate location, which offers us both test data and operational experience. The monitor (Fig. 11) includes both gamma-ray and neutron detectors that are spread over an area covered by medium-size vehicles that stop at the guard station for exit clearance.

B. Gamma-Ray Detectors

Early in our study of gateside monitors, we measured the response of two detector arrays--one commercial, the other experimental--to shielded natural enrichment UF_6. The commercial detector array we used for the measurements was from a Tom Scurry Associates personnel monitor; we made the detector array identical to that used in Tom Scurry Associates vehicle monitors by using only four of eight small NaI(Tℓ) scintillators in the personnel monitor detector columns. The other detector array was part of a prototype Los Alamos personnel SNM monitor that uses Nuclear Enterprises* NE-110 plastic scintillators.[7] These two detector arrays are matched in performance for detecting bare uranium; however, Fig. 12 shows that the plastic detectors have a definite performance edge for detecting shielded natural uranium.

We observed the same trend--better performance of plastic compared to NaI(Tℓ)--later in our vehicle monitor evaluation for detection of PuO_2 and HEU in vehicles. The reason for the difference in performance is that whereas the counting efficiency of both detectors is about the same at low energy, at higher gamma-ray energy the counting efficiency of the plastic detector is greater than the efficiency of NaI(Tℓ). Shielding material removes low-energy radiation emitted by SNM more effectively, leaving the most penetrating, high-energy radiation to be detected.

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*Reading, England.

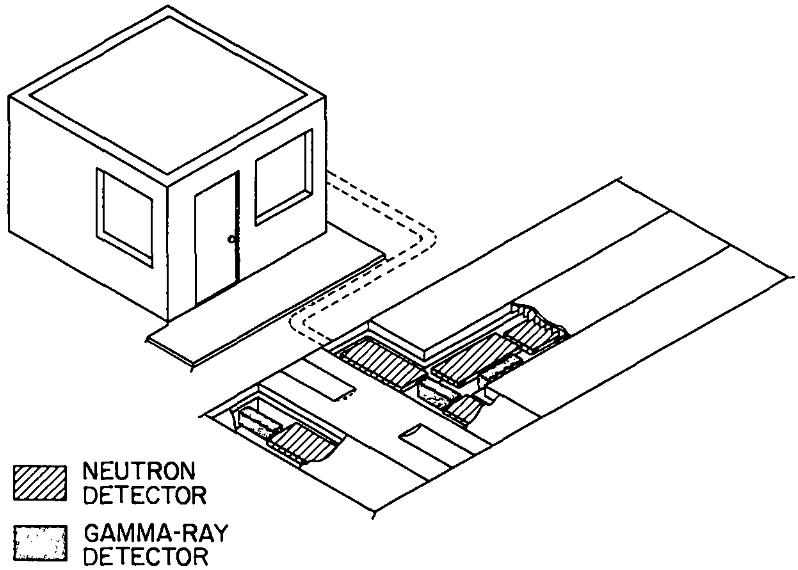

Fig. 11.
The roadbed monitor at Pajarito Site positions both gamma-ray and neutron detectors beneath vehicles that stop to obtain exit clearance. The detectors, located in pits below the pavement, communicate with power supplies and signal-conditioning electronics located in the guard station.

The intrinsic efficiency of the two detector materials (Fig. 13) tells whether a gamma-ray photon entering the scintillator will be counted. The other factor in detection efficiency is the solid angle that describes how much of the radiation leaving a source is intercepted by a detector. The low intrinsic efficiency of the plastic scintillator below 200 keV, where the most intense uranium radiation lies, makes it necessary to use a much larger solid angle for plastic than is necessary for NaI(Tℓ). There is no cost penalty in using a larger detector area (hence, a larger solid angle) for the plastic detectors because plastic is inexpensive relative to NaI(Tℓ). The resulting large detector arrays actually have a distinct benefit in their more uniform spatial response. When the relative size of the detector solid angle is included, the total efficiency curves cross in the uranium radiation region (Fig. 14) and the plastic detector total efficiency remains higher than NaI(Tℓ) at higher gamma-ray energy. The higher energy region is where radiation from plutonium and heavily shielded uranium lies. All of our tests of NaI(Tℓ) and plastic scintillators verify that plastic gives the better performance for the price in detecting plutonium or shielded SNM.

For the roadbed monitor, however, we did not use the optimum detector. We used the smaller NaI(Tℓ) detectors, which could be easily encapsulated to fit into the allowed space. They had to be protected from the damp environment in the detector pits. The detectors were cylindrical in cross section to obtain uniform angular response. The one in Fig. 15 has a background radiation shield and insulating material to limit thermal stress. We used a total of eight gamma-ray detectors in the roadbed monitor to provide fairly uniform sensitivity over the monitored area.

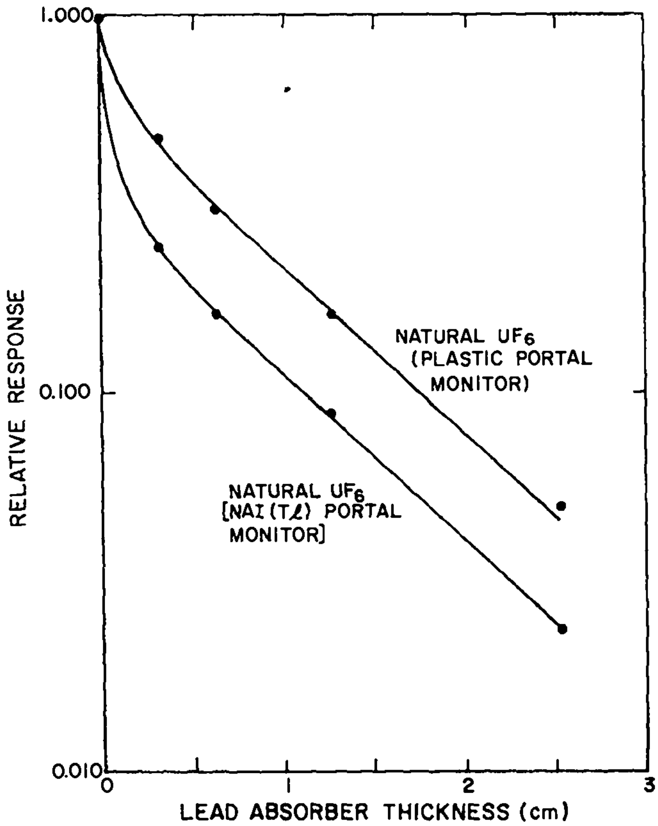

Fig. 12.
The response of NaI(Tℓ) and plastic scintillators to radiation from shielded uranium is quite different. Shielding hardens the gamma-ray spectrum; the plastic scintillator has relatively higher detection efficiency for the harder radiation.

C. Neutron Detectors

The neutron detectors for the roadbed monitor were BF_3 proportional counters backed with polyethylene moderator. These counters provided the required detection efficiency at modest cost. The counters were arranged in assemblies of eight; Fig. 16 shows such an assembly next to a completed gamma-ray detector. Detector sizes and other pertinent information are given in Sec. VI. Figure 17 shows the entire detector array for the roadbed monitor before installation.

The shape of the array in Fig. 17 is designed to fit the footprint of the vehicles that pass through the gate at Pajarito Site. The array is about 3 m wide by 6 m long. Detectors are placed where they will not be covered by the tires of vehicles undergoing monitoring (Fig. 18). The surface area of the monitor accommodates the most common, medium-size vehicles; however, longer vehicles can be monitored in two segments: the front of the vehicle first, then the rear after the vehicle is repositioned on the monitor.

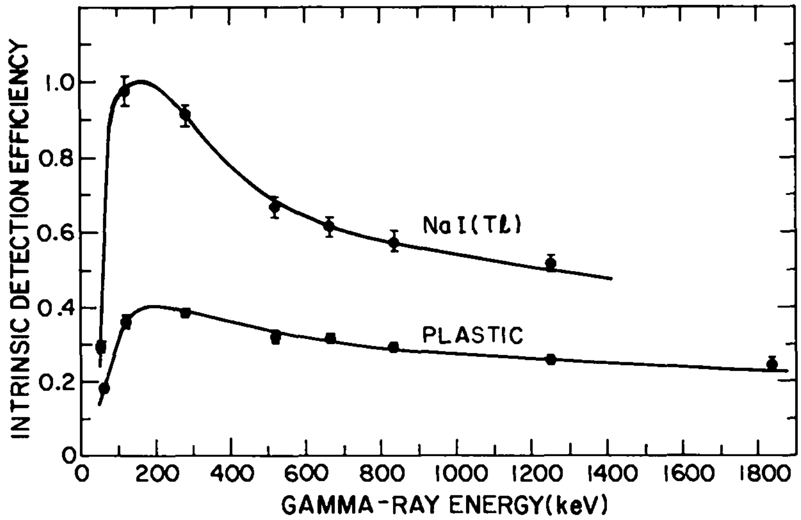

Fig. 13.
These plots compare the intrinsic detection efficiency of NaI(Tℓ) and plastic scintillators. The particularly poor intrinsic response of plastic below 200 keV requires that a larger solid angle (thus, area) be used than would be the case for NaI(Tℓ).

V. DETECTION LOGIC

A. Basic Logic

A radiation monitor detects SNM by comparing the average radiation background B in the unoccupied monitor to a measurement M when the monitor is occupied. To avoid false alarms, the comparison must take into account the statistical accuracy of both the background determination and the occupied measurement. Background measurements made for relatively long periods of time have little statistical variation, hence the major statistical variation is in the occupied measurement. In vehicle monitors that use a relatively long monitoring time, the background determination may be for a period only twice as long as the monitoring period. Then the standard deviation of the comparison includes a contribution from both the background and the monitoring process. Hence, the standard deviation is

$$\sigma = \left(\sigma_B^{\ 2} + \sigma_M^{\ 2}\right)^{0.5} ,$$

where σ_B is the standard deviation of the average background and σ_M is the standard deviation of the monitoring count. The result, in the case where the background count is twice as long, makes the total standard deviation equal to $(1.7)B^{0.5}$.

The alarm increment is a few standard deviations of the background to achieve a low false-alarm rate. The increment may be only a few percent of background, which is about the same magnitude as the suppression of background caused by a vehicle when the roadbed monitor is occupied. For example, a 4σ-alarm-level increment in the roadbed monitor is about 3% of a

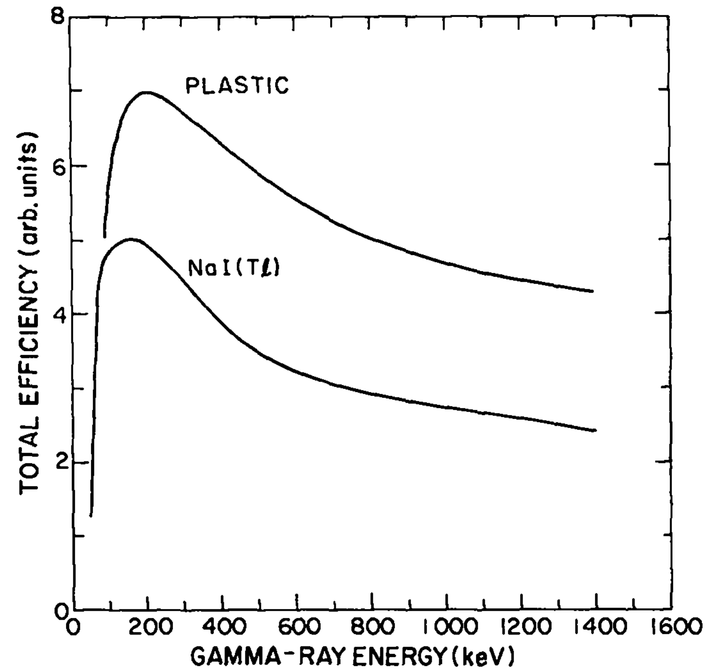

Fig. 14.
The relative total efficiency of NaI(Tℓ) and plastic scintillators includes a solid angle factor that relates the amount of scintillator that must be used to obtain equal performance at low energy. The reason that plastic scintillator monitors perform better for shielded SNM is that radiation from shielded samples lies in the higher energy region where the relative efficiency of plastic is higher.

50-s monitoring count whereas occupancy by a vehicle typically also reduces the background count by 3%. Thus, 6% of unoccupied background, about 8σ, is needed to produce an alarm. As a result, false alarms are infrequent; however, the sensitivity to the presence of SNM is also reduced more than necessary.

A scheme to compensate for the count-rate reduction in the occupied roadbed monitor makes use of an occupancy sensor to initiate monitoring only when a vehicle is present. Then the monitoring calculation uses the measured mean background less some amount that represents the expected reduction in background caused by the presence of the vehicle. We determined an average background reduction of 3% of the unoccupied background for most vehicles using the roadbed monitor. This reduction is larger than the typical 1.5% reduction in occupied personnel doorway monitors, but less than the maximum background reduction in vehicle portals, as large as 27% in our studies. Part of the 3% reduction was included in the logic calculation for the roadbed monitor. Variation in the sizes of vehicles and in the way vehicles enter and park caused differences in the amount of vehicle shielding; we established that safe compensation is only

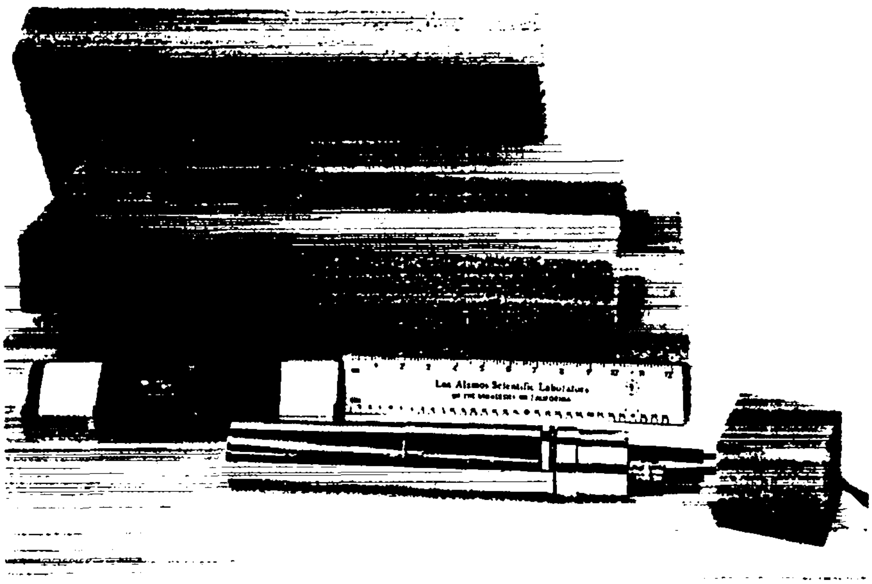

Fig. 15.
The NaI(Tℓ) detector used in the roadbed monitor has a lead background shield, a thin cadmium thermal neutron shield, and insulation. When the detector is assembled, the insulation is covered with a waterproof layer of fiberglass and resin.

about one-third of the measured reduction, or 1%. Thus, for the roadbed monitor, we used an occupied alarm level of A = 0.99B + 4σ and, in general, with an observed background reduction

$$F = \frac{B_{occupied}}{B} \quad ,$$

we calculate

$$B_{occupied} = [1 - 0.33(1 - F)]B$$

and

$$A = B_{occupied} + 4(B_{occupied})^{0.5} \quad .$$

The increase in σ that was mentioned earlier is incorporated in the safe compensation factor in this case.

Experience with a vehicle portal monitor demonstrates a much larger background reduction for any vehicle and a large variation of background reduction with vehicle sizes. The reduction values range from about 10% for the smallest vehicles to 27% for tractor-trailers. In later calculations in Sec. VI, we assume a uniform vehicle size and allow one-third of the observed suppression. This procedure is useful for comparing detector types, but

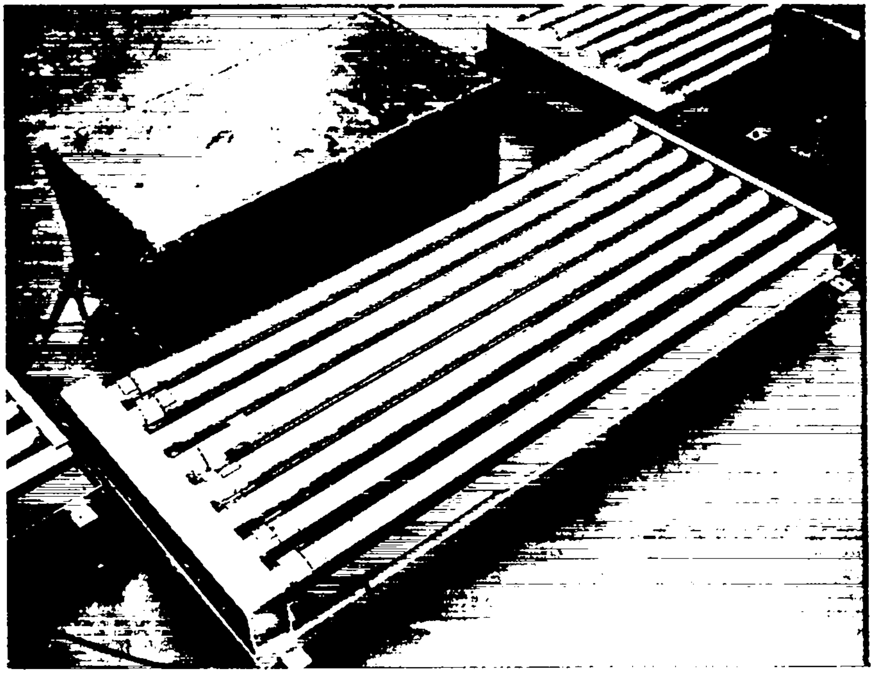

Fig. 16.
The BF_3 neutron proportional counters are mounted in groups of eight atop polyethylene moderating material. The box in the background is an encapsulated gamma-ray detector.

precludes a valid comparison between vehicle portals and the roadbed monitor in cases where the size of vehicles to be monitored varies widely.

B. Count Times

Residence times in monitors are often set by factors that are independent of performance goals. For instance, personnel monitors often are placed where free traffic flow must be maintained and monitor counting time for people in transit may be as short as 0.5 s. However, the residency time is an important factor in detection sensitivity. For example, the signal required to alarm the monitor in a simple case occurs when the signal counts equal the increment added to the mean background. Using $\dot{S}$ and $\dot{B}$ for signal and mean background count rates, respectively, an alarm condition happens when $\dot{S}t = N(\dot{B}t)^{0.5}$, where t represents the count time. Now, the background rate $\dot{B}$ is constant, hence the signal rate needed to just cause an alarm varies with count times, and can be expressed as

$$\dot{S} = N(\dot{B}/t)^{0.5} \quad .$$

Thus, longer monitoring count times reduce the signal count rate that is needed to cause an alarm and make the monitor sensitive to smaller sources. A drawback to excessively long count times is that sometimes the background itself can vary slightly during a monitoring period and cause false alarms. We have chosen to use a count time of 50 s for the roadbed monitor

Fig. 17.
The detector assemblies and cabling used in the roadbed monitor are laid out in the pattern of the detector pits.

because that length of time is about the average manual search duration;[9] background variation during the time it takes to process a queue of vehicles is usually not noticeable.

The large amount of background reduction in vehicle portals complicates simple analysis. The large signal required to overcome background reduction (Fig. 6) becomes the most important factor in analyzing monitor performance. In the general case where the range in vehicle size makes compensation impossible, the signal required to alarm is, almost entirely, that needed to restore the reduction of the background. Hence, both the residence time and the size of the detectors become much less important. In general use, vehicle portals gain nothing from extended counting periods and achieve about the same sensitivity for slow-moving traffic as for vehicles that park for long periods. A vehicle moving slowly through the vehicle portal brings each of its parts close to the detectors, in contrast to a stationary vehicle whose extremities are at some distance from the detectors. Proximity compensates for the shorter residence time.

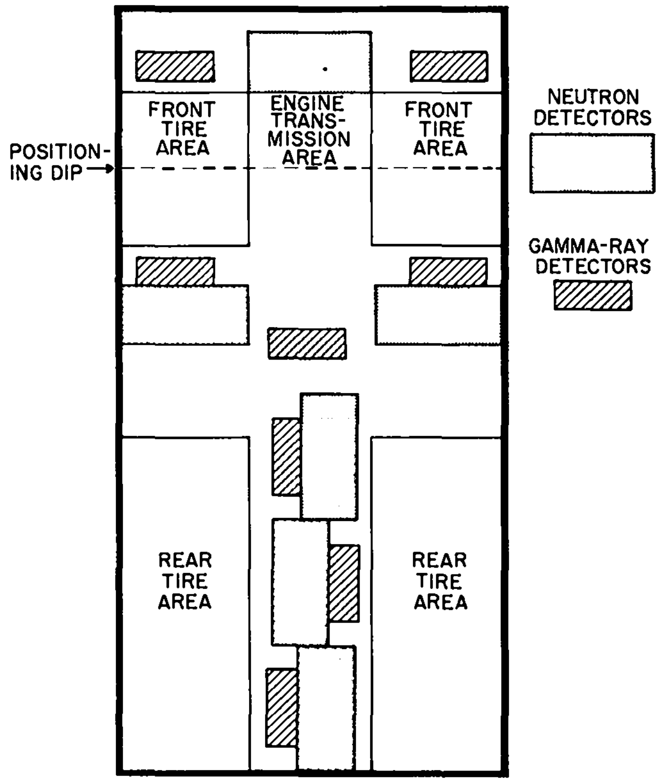

Fig. 18.
The detectors in the roadbed monitor are placed in a 3- by 6-m area where they will not be covered by the tires or the heavy metallic portions of a vehicle undergoing monitoring. The pattern was derived from measurements of 13 government vehicles in use at Los Alamos.

C. Other Logic Schemes

Another approach to monitoring[10] makes use of a net count that is obtained by subtracting from the occupied measurement a mean background taken from measurements made for equal time periods before and after occupancy. We applied the technique to the roadbed monitor, but found that background variation during the period required to monitor queues of vehicles gave many false results, particularly when the after-occupancy background was not obtained until tens of minutes after the initial occupancy. Therefore, we do not recommend the scheme for vehicle monitors unless background is absolutely constant. That is seldom the case for outdoor monitors because even rainfall changes background levels. Rain washes dust with attached radioactive ^{222}Rn daughters from the atmosphere, increasing the monitor background for an hour or two. Figure 19, an example of rainfall background variation, was obtained with a separate, upward-looking reference detector that is a part of the roadbed monitor system.

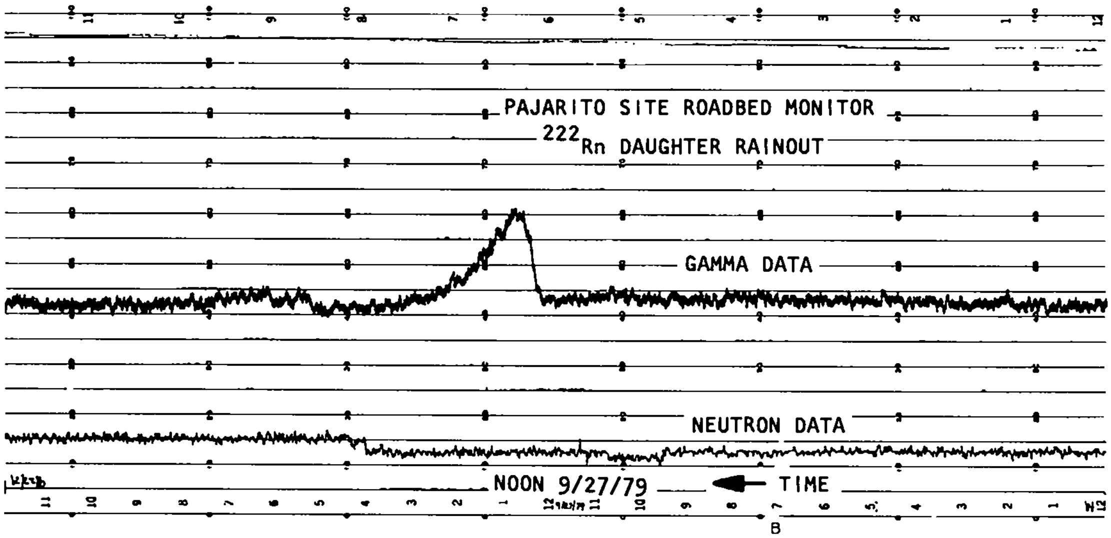

Fig. 19.
The strip chart from the roadbed monitor system shows the time response of an upward-looking background monitor. Time increases toward the left. A short intense snowfall removes ^{222}Rn daughter-laden dust from the atmosphere and increases the gamma-ray count rate. The count rate decays to normal in the next hour or two.

VI. COMPARISONS OF MONITOR PERFORMANCES

A. Fixed Monitors

The first step in our comparative study of vehicle radiation monitors was based on static measurements in fixed monitors. These preliminary measurements, begun in September 1978, used two gateside detector arrays. One was a Tom Scurry Associates commercial version with four 5-cm-diam by 2.5-cm-thick NaI(Tℓ) detectors; the other was from a Los Alamos personnel monitor with four 5-cm-diam by 91-cm-long NE-110 plastic scintillators.[7] Both of these arrays were tested indoors in three configurations ranging from a separation of 3.6 m to 7.2 m between the two detector columns that form a monitor. The arrangement was the same as in Fig. 4, but located indoors.

The third fixed monitor selected for our comparison, the Los Alamos roadbed monitor, went into operation in February 1979. It has eight 5-cm-diam by 15-cm-long NaI(Tℓ) detectors spread over the vehicle footprint and six BF_3 neutron detector arrays (Fig. 16), each containing eight 5-cm-diam by 91-cm-long proportional counters.

The comparison of these three monitors assumed a long monitoring period (50-s count time) and compensated for one-third of the occupied background reduction. The vehicle chosen to obtain data for the comparison was a Ford 1-ton recreational van (Figs. 3 and 4), which is representative of most traffic at Pajarito Site. Other vehicles, including some that challenge the capability of any monitoring equipment (garbage and dump trucks), were examined to determine the relative performance of the monitors. The limitation on what vehicle monitors can detect was demonstrated by a Clark

15-ton dump truck containing 10 tons of gravel with a plutonium sample imbedded in the gravel. No discernable gamma-ray or neutron signal from the sample could be detected with fixed or hand-held monitors. This series of measurements was completed in October 1979 except for last-minute measurements that were done in October 1980 to complete the data needed for this report.

Our static comparisons (Table III) include results for two different spacings of the vehicle portal monitors; the wider spacing is used for two-lane traffic, the narrower for a single lane. The important comparisons in static performance for the monitors, besides detectable mass, are the background reduction caused by occupancy and the reduction in detected source counts caused by attenuation in vehicle construction materials.

From Table III one sees that the plastic portal detectors exhibit the best performance and can detect the smallest amounts of SNM, as we expected. Both of the portals have lower minimum detectable masses* than the roadbed monitor in this comparison. The reason is that the roadbed monitor as it now exists is one-sided; attenuation of the SNM radiation occurs when thick metal is placed between the SNM in the vehicle and the detectors or when SNM is placed at the top of the vehicle, well away from the detectors. Note in Table III that about three times less vehicle transmission was measured in the roadbed monitor because the vehicle contained a motor generator and voltage regulator module that shielded the test source (Fig. 20). The use of overhead detectors would have reduced the attenuation to about 0.29 and greatly improved the monitor's performance.

The Ford 1-ton van selected for these tests (Figs. 3 and 4) was about the correct height (2 m) to position test sources at the maximum distance from the roadbed detectors. Its height is about midway between the roadbed detectors and the position that the overhead detectors would occupy. That makes the top of the van a worst test case; on the other hand, the vehicle is not representative of mixed traffic. Monitoring smaller vehicles would have produced better results in the roadbed monitor. This is important because, as mentioned earlier, the ability to compensate for the background reduction in the vehicle portals depends on using vehicles of one size. Mixed traffic limits the amount of compensation and makes the roadbed monitor performance appear better.

In the roadbed monitor, the performance of the neutron system for detecting plutonium is slightly better than that of the gamma-ray system; however, in routine use, we found that microphonic signals caused by vibrations during vehicle passage over the monitor increased count rates enough to cause alarms. It was necessary to increase the alarm level to 20σ to obtain a reasonable false-alarm rate, which reduced the detectable plutonium mass to well below the capability of the gamma-ray system.

A final consideration in evaluating the performance of the roadbed monitor is the addition of overhead detectors by means of a canopy

*The minimum detectable mass is the least amount of SNM in compact form that can be detected when placed in a vehicle at the location where SNM is hardest to detect. That location may be most distant from the detectors or may be well shielded by vehicle structure.

TABLE III

RESULTS OF STATIC COMPARISONS

Monitor	Occupied Spacing (m)	Background[a] Count Rate (s^{-1})	Source	Relative Detectable Mass	Background[b] Reduction	Vehicle[c] Transmission
NaI(Tℓ) portal	7.3	250	HEU[d] PuO_2	1.00 1.00	0.93	0.17
	3.6		HEU[d] PuO_2	0.71 0.44	0.89	0.18
Plastic portal	7.3	2500	HEU[d] PuO_2	0.88 0.61	0.96	0.22
	3.6		HEU[d] PuO_2	0.59 0.28	0.89	0.25
Roadbed gamma-ray (one-sided)	—	900	HEU[d] PuO_2	1.18 1.61	0.97	0.068
Roadbed neutron	—	60	HEU[d] PuO_2	— 1.39 (4σ) 15.4 (20σ)[e]	0.99	—
Roadbed gamma-ray (estimated two-sided)	—	900[f]	HEU[d] PuO_2	0.16 0.06	probably 1	0.29

[a]In a nominal 20 μR/h background.

[b]The ratio of occupied to unoccupied background.

[c]Ratio of counts detected with source in vehicle to source alone.

[d]HEU is 93% enriched uranium metal; PuO_2 has 6% ^{240}Pu content.

[e]The larger alarm increment was used to avoid false alarms caused by microphonics.

[f]Separate logic path for overhead detectors.

(Fig. 21). The final entry in Table III is an estimate of how the gamma-ray detectors will perform with overhead detectors. A canopy should eliminate the occupied background reduction. We propose that separate electronics and logic be used for each of the overhead and underground detectors. Then with signals for what we estimate would be the attenuation of intervening materials and signal reduction from detector-source distance for an overhead detector, we calculate much better performance for the two-sided roadbed monitor than for either of the vehicle portals.

Another improvement in a two-sided roadbed monitor could be made in neutron detection. With altered underground detectors that reduce microphonics (this can be done by including signal-conditioning electronics in each

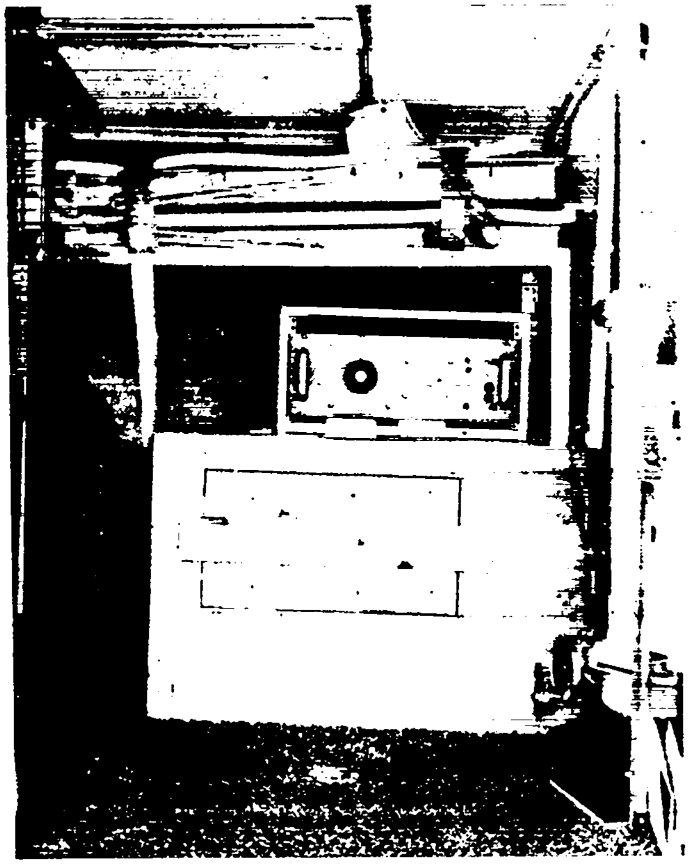

Fig. 20.
The test source, contained in the tagged can inside a Ford 1-ton van near the roof, is shielded by the voltage regulator module and a gasoline motor generator below it. Overhead detectors would have an unobstructed view of the test source.

detector unit) and with overhead detectors, the performance of the neutron system also should exceed that shown in Table III for the existing monitor.

B. Vehicle Portals

On the basis of the foregoing static comparison and because a canopy would not be incorporated in the near future, in 1981 we continued our investigation by examining vehicle portals in more detail. We designed and had fabricated a new prototype vehicle portal monitor (Fig. 4 and Appendix A) with much wider plastic scintillators (Fig. 22) and a control module with logic similar to the roadbed monitor logic. We examined this vehicle portal in detail for use as a personnel monitor[11] as part of the initial trials. We then compared its performance to mock-up vehicle portals using larger 12.7-cm-diam NaI(Tℓ) detectors than were previously used but the same plastic detectors. The mock-up vehicle portals were reconfigured to provide adequate monitoring of tall vehicles. Next to the new vehicle portal monitor at the outdoor test location (Fig. 23), a wooden structure supported the tall detector arrays of the mock-up portals.

1. Background Reduction and Detector Spacing. The vehicle portal tests took place at several detector spacings. Vehicle background suppression diminished with increased spacing, but varied with vehicle size, as Table IV illustrates. A second factor in changing the detector spacing is the reduction in the detected source intensity with wider spacing. For a Ford 1-ton van in the new vehicle portal, we established best performance when the detectors were 4.3 m apart, in the spacing range 3.7 to 5.6 m. Performance degrades rapidly at spacing narrower than 4.3 m and is only slightly reduced for wider spacing. We carried out our vehicle portal comparisons at a detector spacing of 4.9 m.

2. Vehicle Portal Comparisons. To compare the vehicle portals, we calculated the expected performance based on background reduction and net SNM source intensity observed during scanning measurements. A series of measurements, conducted with different vehicles and different types of SNM, gathered data—similar to the curves in Fig. 24—for each case. These data were collected at 91-cm intervals during vehicle pauses while a series of computer-controlled scalers conducted a radiation count. These scalers recorded the performance of each monitor in separate shielded-plutonium and shielded-uranium energy windows. The information obtained from the scans is sufficient to analyze both static and dynamic performance.

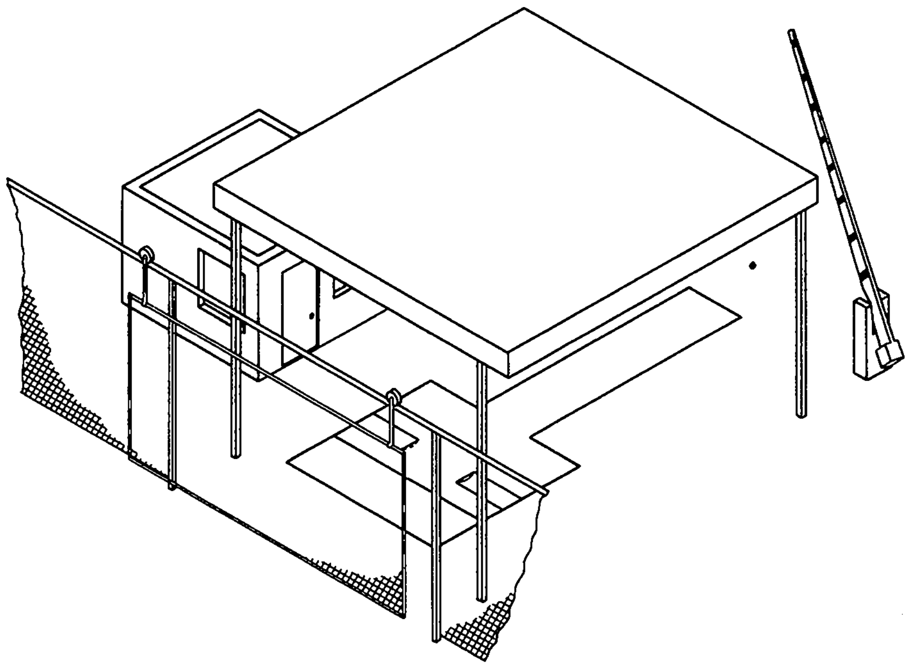

Fig. 21.
An overhead canopy added to the existing roadbed monitor would allow detectors to be placed where they could effectively monitor the top of tall vehicles. An electrically operated gate and a crash barrier trap vehicles during the monitoring period.

Fig. 22.
The detectors for the new vehicle portal monitor are wide plastic scintillators mounted in cabinets with photomultipliers and light pipes overlapping halfway up the column.

The performance comparison simply selects the integrated background suppression and signal over a distance of about 4.5 m, the distance that would be covered in 2 s by a vehicle travelling at 8 km/h, and calculates the least detectable amount of SNM. Table V compares the relative minimum amounts of material needed to cause an alarm in the different monitors. The indicated quantities depend on many factors, including ambient radiation background, size of vehicle, detector response to emitted and scattered radiation, vehicle source shielding, and vehicle speed.

The trend in Table V is for the new vehicle portal to exhibit better performance than the mock-up portals for lightly shielded SNM, as would be the case for smaller vehicles. This trend reflects the lack of excessive background suppression that permits the large area detectors to be effective.

Larger vehicles with heavily shielded sources produce equal performances in both the mock-up plastic portal and the new vehicle portal. Performance in the NaI(Tℓ) mock-up is considerably degraded because

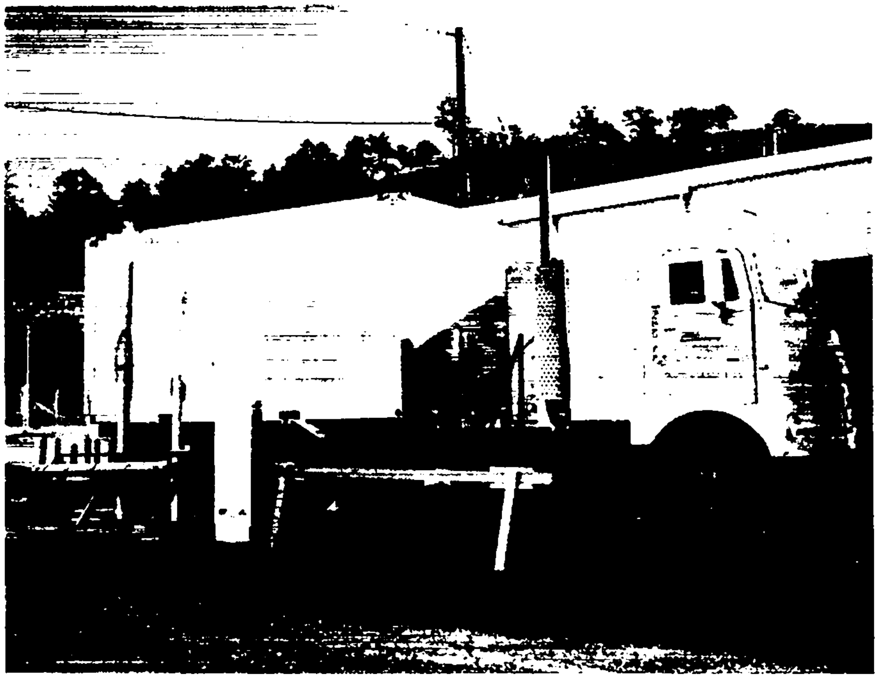

Fig. 23.
Vehicle portal tests included tests of a new prototype monitor with wide plastic scintillators and two mock-up vehicle portals, one with plastic scintillators and one with NaI(Tℓ) scintillators. The vehicle undergoing monitoring is the Los Alamos Secure Vehicle.

NaI(Tℓ) has poorer detection efficiency for the higher energy radiation transmitted through the heavy shielding.

A final point concerning Table V is that the size of the vehicles that can be monitored differs for the new prototype vehicle portal (intended for medium-size vehicles) from the mock-up portals, which are tall enough to handle all vehicles.

3. Logic for Vehicle Portals. We have just compared vehicle portals for monitoring vehicles in motion. The performance of the monitors was calculated from the most intense part of the signal observed during vehicle passage (Fig. 24). The maximum signal would probably not occur if the vehicle had remained stationary during the monitoring period. Stationary monitoring might position the diverted SNM far from the detectors (Fig. 25) and result in lower signals with correspondingly decreased performance even though longer counting times could be used. Vehicle motion during monitoring ensures close proximity of diverted material and detectors.

Monitoring vehicles in motion requires some control over the vehicle passage speed. Monitor performance decreases with increasing speed. Thus, some means of controlling speed is required. We propose a vehicle trap, consisting of a fenced area with entry and exit gates. The trap requires vehicles to stop at a closed gate; when the gate opens, the vehicle can

TABLE IV

BACKGROUND SUPPRESSION IN VEHICLE PORTAL MONITORS

Motor Vehicle	Occupied Background[a] at 3.7-m Spacing, New Vehicle Portal	Occupied Background at 4.9-m Spacing		
		New Vehicle Portal	Plastic Mock-Up	NaI(Tl) Mock-Up
Datsun pickup truck	0.936	0.940	0.976	0.933
Chevrolet pickup truck	0.900	0.922	0.926	0.908
International Travelall	0.861	0.904	0.910	0.866
Ford 1-ton van	0.840	0.909	0.900	0.855
Step van	—	0.896	0.910	0.831
Los Alamos Secure Vehicle	—	0.783	0.791	0.712
DOE Safe, Secure Transport	—	0.730	0.777	0.655

[a]The occupied background is expressed as a fraction of the unoccupied background.

slowly move inside to the closed exit gate while being monitored. We believe that this approach can effectively limit maximum speed to 8 km/h, the rate we used to calculate the values in Table VI.

The results in Table VI are in agreement with those expected from the information in Table III. Improvement for the new vehicle portal results from the larger solid angle of the detector in the new vehicle portal. The detector size has greatest influence on monitor performance for monitoring these medium-size vehicles. Other unseen differences between the three types of portals compared in Table VI are that the mock-up portals have the capacity to monitor tall vehicles.

C. Hand-Held Versus Fixed Monitors

Following the initial fixed-monitor comparison, in October 1979 we began a comparison of the roadbed monitor to a hand-held monitor. In addition to comparing the performance of the two monitors, we wanted to

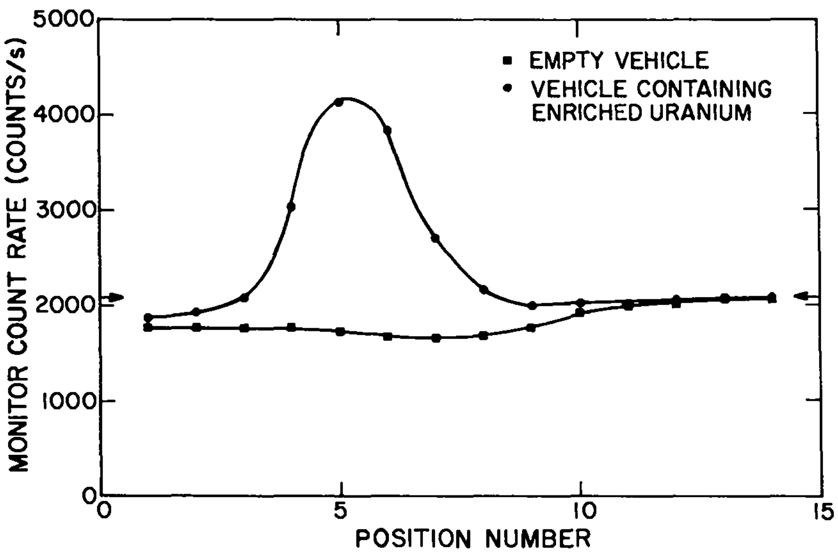

Fig. 24.
Scanning measurements are carried out as a vehicle, which may or may not contain SNM, moves past the vehicle portal detectors, stopping every 91 cm for radiation intensity measurements. The lower curve displays the background suppression caused by an empty vehicle; the upper curve is for SNM inside the vehicle. Performance calculations use the data at the five positions that exhibit the more intense source count rate.

determine typical monitoring times and effectiveness levels that are obtained by present operational practice at a working installation.

1. Initial Tests. Our comparative study observed hand-monitoring practices used by the Protective Force at the vehicle exit to Pajarito Site. To maintain the accustomed monitoring routine at the exit, we obtained permission from the Security Office and the Nuclear Materials Division at the Los Alamos National Laboratory to carry SNM out of Pajarito Site in a US government vehicle. At the start of the study, the Protective Force did not know that we were removing SNM from the site. We placed bare SNM samples in the cargo space of an International Travelall (Fig. 26). We monitored the vehicle ourselves to verify that the SNM could be detected with a hand-held personnel/vehicle monitor (PVM) of the type in routine use at the gate. We determined a number of positions for the PVM both inside and outside the vehicle from which the SNM could be detected. During these initial tests, we varied the amount of SNM being removed and observed the amount of time that the vehicle was detained, the thoroughness of the search, and the outcome.

2. Second Test Period. Our second approach was to ask that our penetration test activity be announced at each morning formation of the Protective Force. We found that vehicles were detained longer and searches were more thorough. Interest was high enough for many inspectors to take

TABLE V

RELATIVE MINIMUM AMOUNTS OF SNM
THAT CAN BE DETECTED IN VEHICLE PORTALS

Vehicle	New Vehicle Portal	Plastic Mock-Up	NaI(Tl) Mock-Up
	Minimum Quantity of Plutonium Detected[a]		
Step van	1	1.73	3.12
International Travelall	1	1.69	1.87
Ford 1-ton van	1	2.16	2.27
	Minimum Quantity of HEU Detected[a]		
Step van	1	1.44	1.70
Ford 1-ton van	1	1.74	1.63
Los Alamos Secure Vehicle	1	1.25	1.21
	Minimum Quantity of Mixed HEU and Natural Uranium, Moderately Shielded[a]		
Ford 1-ton van	1	1.87	2.21
DOE Safe, Secure Transport	1	1.38	1.41
	Minimum Quantity of Mixed SNM, Heavily Shielded[a]		
Los Alamos Secure Vehicle	1.02	1	1.50
DOE Safe, Secure Transport	1.07	1	1.65

[a]The quantities are normalized to the least amount detected in each case. Portal detector spacing is 4.9 m and background intensity is 20 μR/h.

every opportunity to test the operation of each of the two hand instruments at the station. Interest was stimulated whenever a detection took place or a nondetection was announced. This testing phase was a well received on-the-job training experience for many inspectors.

3. Subsequent Performance. At this point we wrote a recommended procedure for searching vehicles and personnel (Appendix B) and suggested that DOE provide training and supervision to try to make inspector performance more uniform. Training for the entire Protective Force is very important because the inspectors rotate through all the entry/exit stations at Los Alamos and may not be familiar with the procedures at Pajarito Site when they are assigned there. The recommended inspection procedure was incorporated into the Pajarito Site station orders, but the thoroughness of the vehicle searches remains variable. The evolution of the average length of time that vehicles spend waiting to depart from Pajarito Site indicates how the thoroughness of monitoring changed during the three stages of our penetration tests. Figure 27 shows that hold times increased during the

Fig. 25.
Vehicle portals are best used for monitoring vehicles in slow motion. This tractor-trailer—a DOE Safe, Secure Transport—is so large that stationary monitoring would not be effective because most parts of the vehicle are too far from the detectors.

TABLE VI

PLUTONIUM SENSITIVITY OF VEHICLE PORTALS[a]
FOR 8 km/h PASSAGE SPEED

	Relative Plutonium Sensitivity		
Vehicle	New Vehicle Portal	Plastic Mock-up	NaI(Tℓ) Mock-up
International Travelall	1.00	1.67	1.88
Ford 1-ton van	2.31	5.00	5.24
Step van	1.29	2.20	4.03

[a]Portal spacing is 4.9 m and background is 20 μR/h.

Fig. 26.
The International Travelall had SNM samples in the rear cargo space. When it stopped for exit clearance from Pajarito Site, it was searched manually by the inspector using a PVM and automatically by the roadbed monitor.

second test period, but returned to pretest values afterwards. Evidently, the inspectors spent more time monitoring with the hand-held instrument when they knew that their effectiveness was being measured. Later, when the daily reminder to monitor thoroughly was removed, holding times decreased. An important conclusion is that motivation is important to thorough searching, hence, supervision is as important as training.

D. Strong Points and Drawbacks of Monitors

Each monitor has its strong points and its drawbacks. These include factors that affect how well the monitor fits in with preexisting operation, how the monitor is affected by possible shielding ploys, and how easily monitor operation can be maintained.

1. Vehicle Portal. The vehicle portal monitors impose space restrictions when the detectors are placed at their narrowest separation, 3.6 m. Narrow detector spacing requires that traffic flow in a single lane through the monitor without making sharp turns. The hazard of damage to the detectors from automobiles, trucks, or snow plows makes protective guard rails necessary. A final drawback is that vehicle portals suffer most from background suppression, which limits their sensitivity. Advantages of vehicle portal monitors are that they are the most economical fixed

monitors, are easily installed, can have reasonable sensitivity, and are easily accessed for maintenance.

2. Roadbed Monitor. The roadbed monitor presents little obstruction to normal traffic flow, but it does require extensive construction on site. The detectors are well protected, but dwell in an extremely humid environment; access for maintenance is inconvenient. Overhead detectors are required for tall vehicles, making a canopy or other overhead support mandatory. With the canopy, the roadbed monitor is the most effective as well as the most expensive of all the vehicle-monitoring devices.

3. Hand-Held Monitor. Hand-held monitors such as the PVM are inexpensive, require no installation, and may be transported easily to a service area for maintenance. The principal drawback is the human factor consideration: the inspector who performs the search must be well trained, well disciplined, and experienced. The inherent high sensitivity of the instrument is achieved when well-trained inspectors devote adequate time to a thorough search.

4. General Problems. Hand monitoring requires training and supervision to maintain inspector motivation but in addition, training can point out steps that are easily overlooked. Searching empty spaces or a driver who has stepped away from the vehicle may require prompting by a checklist (Appendix B) because these steps simply don't come to mind, particularly to untrained searchers. Another handicap is the lack of support equipment to aid searching the top of a tall vehicle or underneath a vehicle with little ground clearance.

As we mentioned, the current roadbed monitor is one-sided. It can be improved by adding overhead detectors. However, it can also be improved by replacing the NaI(Tℓ) scintillators with plastic scintillators, developing individual logic paths for each detector, and redesigning the detector pits. The existing pits are a significant drawback because their covers must be thick enough to support heavy vehicles; the thick covers attenuate the intensity of the SNM radiation. Redesigned detector pits would support vehicle loads by other means than the pit covers, which could then be thinner, thus enabling higher gamma-ray transmission.

VII. FURTHER WORK

The roadbed monitor could be upgraded by improving drainage and using separate logic for groups of detectors. Alternative detectors, in particular plastic scintillators (both below and above a vehicle), and a data transmission system that allows more than one gamma-ray energy window also are needed.

A new approach to detection logic, suggested by Tom Scurry Associates, was incorporated into a new control module for the roadbed monitor. This control module makes sequential monitoring measurements. First, 20- and 40-s count periods using 2σ and 3σ alarm levels are used. If no alarm occurs at each of these steps, the monitoring ends; if an alarm occurs during the first two steps, a 4σ alarm level is used with a 60-s test. The first two alarm levels have the same source sensitivity but a higher false-alarm rate than the third alarm level. Some fraction of vehicles will pass the first

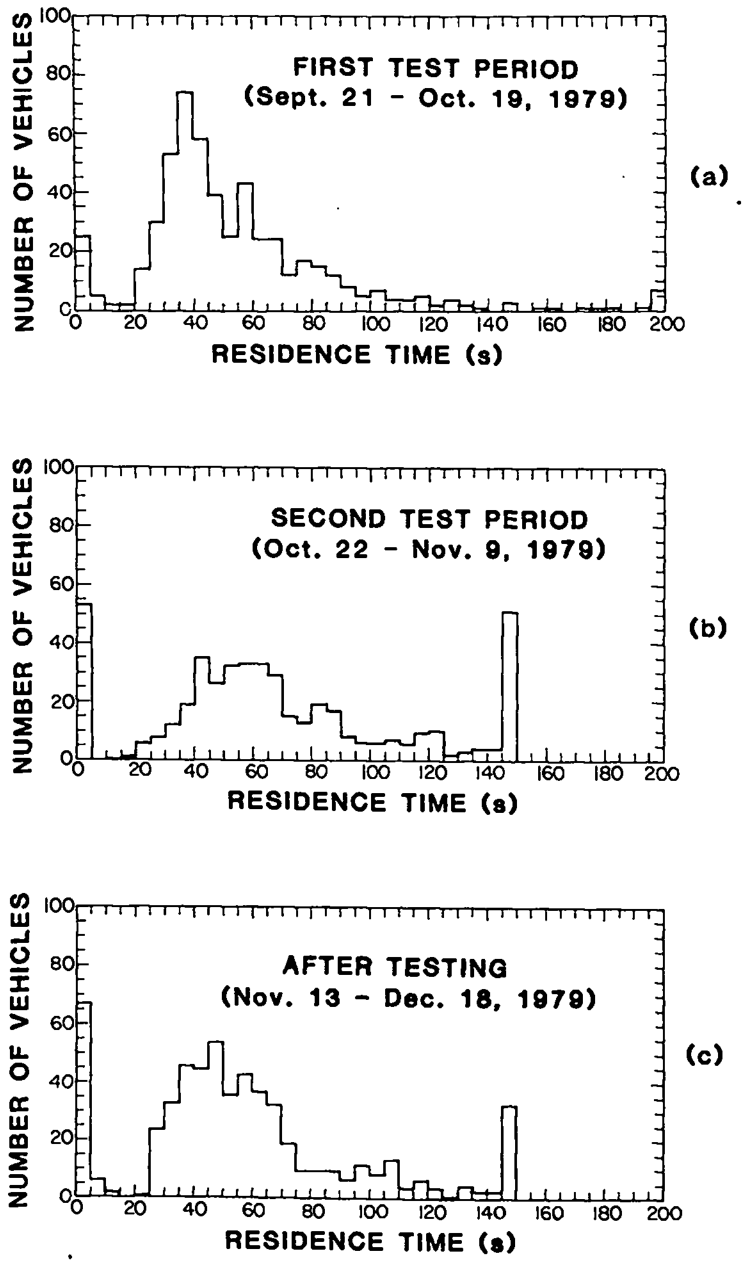

Fig. 27.
(a) The residence time for vehicles undergoing manual search during initial testing averaged 40 s; (b) it increased to about 60 s during the second stage when inspectors knew that they were undergoing testing; (c) after the test period, residence time returned to near previous values.

tests and be able to leave early. The remainder will stay for the entire period. This control module needs to be evaluated in routine roadbed monitor operation.

Finally, effective monitoring procedures are essential in the routine training program of Protective Force inspectors. If training periods cannot be made available during the normal work schedule, a videotape or written manual for inspectors to study on the job when time is available would be beneficial.

ACKNOWLEDGMENTS

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APPENDIX A

SPECIFICATIONS FOR AN SNM VEHICLE PORTAL MONITOR

This is a specification for a monitor capable of detecting small amounts of SNM in a stationary vehicle located between two gateside gamma-ray detectors. The monitor consists of vehicle presence sensors, vehicle sensor logic, gamma-ray detectors, gamma-ray detector logic, and output devices. A description of each component of this monitor follows. Note that the monitor checks stationary vehicles. During evaluation of this monitor, we found that monitoring vehicles in motion was preferable to monitoring stationary vehicles. We have added notes to the following descriptions wherever component changes are required to allow motion.

VEHICLE SENSOR

Two separate vehicle presence sensors and controllers are needed to determine vehicle presence and direction of motion, incoming or outgoing. For instance, two current loop sensors buried in the roadway may be used to determine when outgoing traffic is present to start the monitoring sequence.

VEHICLE SENSOR LOGIC

The vehicle sensor determines the direction of vehicle motion from vehicle presence sensors. The directional information enables monitoring of outgoing traffic only.

The vehicle sensor logic must use the presence sensor nearest the gamma-ray detectors as an occupancy indicator to inhibit background accumulation from the gamma-ray detectors during presence of both incoming and outgoing traffic.

GAMMA-RAY DETECTORS

Two gamma-ray detectors are required, one on each side of the vehicle that is approaching an exit through a gate in a security fence. Detector separation should be between 3.7 and 4.25 m. Detector enclosures should provide the necessary protection from the weather to permit detector operation within temperature ranges of -30°F to +100°F and during long periods of intense sunlight, heavy rainfall, hail, and snow. Detector enclosures should be equipped with flanges drilled to permit bolting them in place. Easy access should be provided for detector maintenance.

The gamma-ray detector should be of the solid plastic scintillator type, which has an inherent higher detection efficiency for radiation emanating from shielded SNM. The scintillators should be as large as those used in personnel SNM monitors and should be in two parts, each about 1 m long. In use, two detectors are positioned in a column with photomultipliers located at the halfway point (Fig. A-1). Typical Pilot F detector dimensions are 30 cm wide by 3.8 cm thick by 91 cm long with a 23-cm-long light pipe

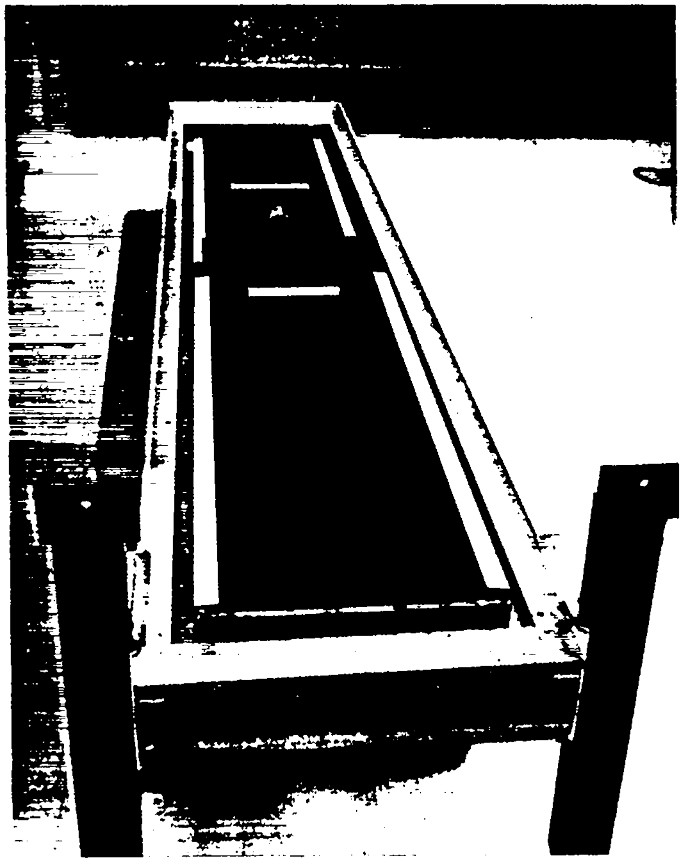

Fig. A-1.
The new vehicle portal monitor detectors are positioned in detector cabinets with the insensitive light pipe and photomultiplier regions overlapping.

and a 3.8-cm-diam 10-stage scintillation photomultiplier. For larger vehicles, it may be better to use two separate sets of smaller detectors.

Provision should be made to balance the output of the detectors by a photomultiplier high-voltage adjustment or a preamplifier gain adjustment.

SIGNAL-CONDITIONING ELECTRONICS

Each detector column must have one low-noise, scintillation-detector preamplifier. A shaping amplifier and single channel analyzer must be used to generate logic pulses for the control logic.

CONTROL LOGIC

The gamma-ray detector logic uses information about the background radiation that is accumulated when the monitor is unoccupied to derive alarm levels. Background intervals are 100 s long; monitoring intervals should be 60 s in stationary monitoring. (Monitoring in motion requires a 2-s-long sliding interval.*)

The alarm level derived from the background data needs to be adjustable in two ways. First, a vehicle occupying the monitor will reduce the background count rate, as seen by the detectors, by perhaps as much as 27%. Second, variation in the alarm level increment is needed. One possibility for achieving the necessary variation is to provide a switch-selectable multiplier for the mean background and a switch-selectable N-sigma or fixed increment to be added to the mean background in the alarm-level algorithm. Usually, a 4σ level for the 60-s count period is needed.

The monitoring period should start automatically when the monitor detects outgoing traffic. The ability to repeat the monitoring interval for stationary vehicles should be available through pushbutton request. At the end of the monitoring period, the accumulated count is compared to the alarm level to determine the appropriate output. It may also be desirable to use separate logic channels for energy windows to detect bare ^{235}U, shielded ^{239}Pu, or shielded uranium.

When the monitor is unoccupied, a test of each new background count must be made against switch-selectable upper and lower limit values. These are expected to be set about 20% above and below the mean background.

Status output should be provided in the electronics module and at a remote panel located outdoors near the detectors. The electronics module requires a numerical display of mean background counts and audible and visual indicators. Only audible and visual indicators are required outdoors. The required indicators are listed in Table A-I.

EXCEPTIONS

Other approaches to the monitoring problem and other performance criteria may be acceptable, but sufficient detail must be given to allow full consideration of exceptions.

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*W. H. Chambers, C. N. Henry, H. F. Atwater, W. E. Kunz, P. E. Fehlau, T. E. Sampson, R. D. Hastings, T. H. Whittelsey, and G. M. Worth, "Portal Monitor for Diversion Safeguards," Los Alamos Scientific Laboratory report LA-5681 (1974).

TABLE A-I

AUDIBLE AND VISUAL INDICATORS

Monitor Condition Indicator	Visual Indicator Light	Audible
Unoccupied	steady yellow	---
Occupied and monitoring count taking place	blinking yellow	---
OK result after monitoring	blinking green	---
Alarm result after monitoring	blinking red	sounding
High-low background alarm or logic malfunction	none--all lights off	---

APPENDIX B

TECHNIQUE FOR HAND MONITORING VEHICLES

This is a 10-step procedure for proper hand monitoring of motor vehicles to detect the presence of SNM. A hand-held SNM monitor that audibly announces detection is used to conduct the search.

1. PREPARATION FOR SEARCH. Have the driver shut off the engine and open the hood, all doors, and trunk lids. Be sure the hand-held monitor is turned on and operating properly.

2. DRIVER AND PASSENGERS. Driver and passengers must stand outside the vehicle during the search. When the vehicle search has been completed and before anyone reenters the vehicle, each person must be searched.

3. HOOD. Move the monitor to within 6 in. of every surface within reach and search the hood itself.

4. ALL DOORS AND TRUNK LIDS. Using the monitor, search the doors, trunk lid, and vehicle interior; search under the front seat, dash, sun-visor, headliner area, and floor; search on and under rear seat, rear floor, rear headliner, and any space behind the rear seat and trunk area. For areas that cannot be entered, search from the outside. Cover the entire surface coming within 6 in. of each point at least once.

5. VEHICLE EXTERIOR. Search the lower part of the vehicle, especially the heavy metal frame. Scan under the bumpers and under the remaining perimeter of the vehicle. Monitor under the vehicle both behind and in front of the wheels.

6. PICKUP TRUCKS. Scan the empty bed for objects attached beneath it.

7. STEP VANS, FLATBED TRUCKS, DUMP TRUCKS. Search any interior space that is accessible and the entire exterior.

8. GARBAGE TRUCKS. Scan under the hood and inside the cab area in addition to the exterior.

9. ESCORTED VEHICLES, PARTICULARLY THOSE WITH A SINGLE ESCORT. These vehicles still require searching even though they are escorted by the Protective Force.

10. LOOK FOR SHIELDING MATERIALS. Search lead or large steel containers and open them if possible.

GLOSSARY

HEU	highly enriched uranium
NaI(Tℓ)	thallium-activated sodium iodide
PVM	personnel/vehicle monitor
SNM	special nuclear material

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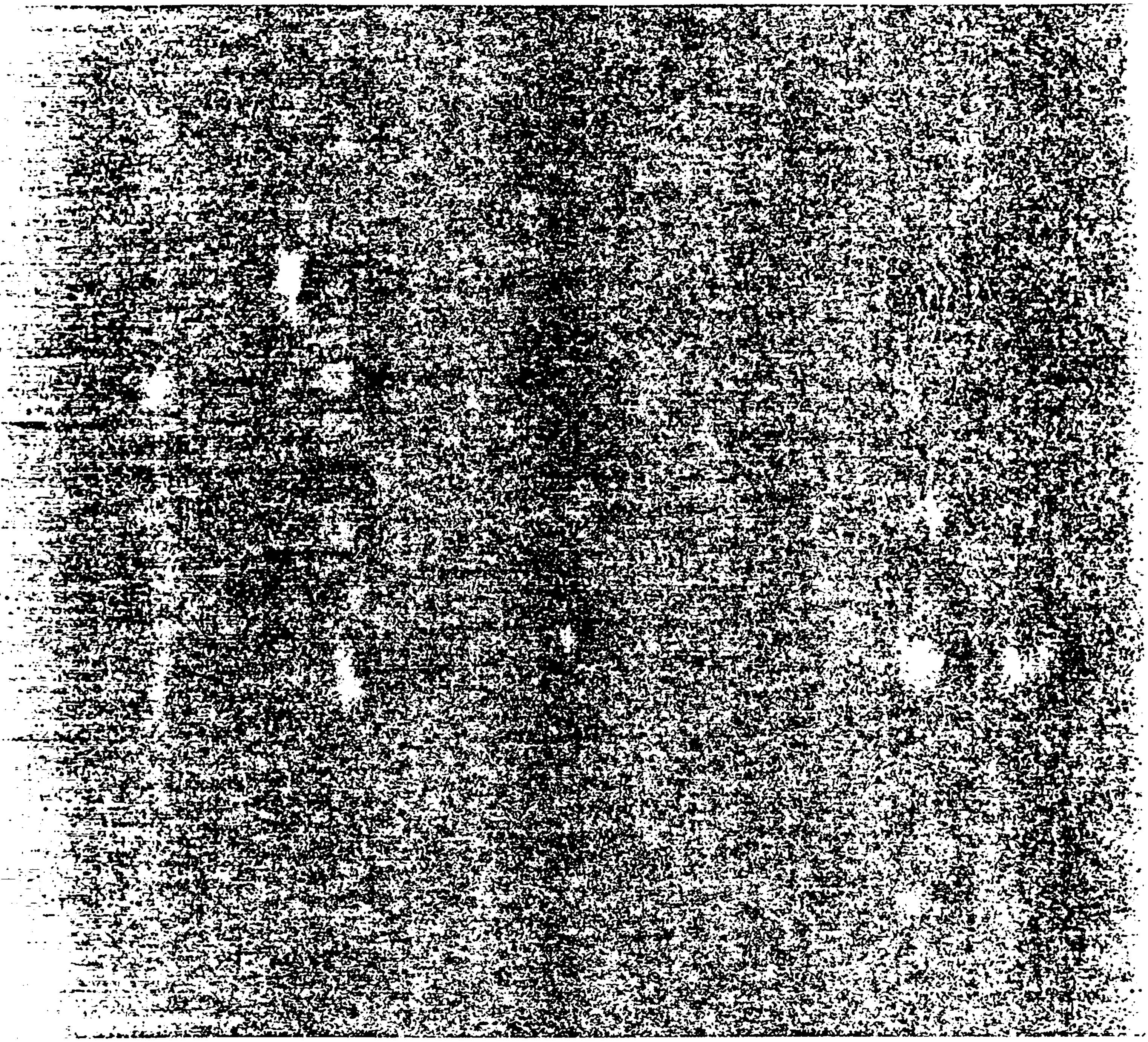

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