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Passive Nuclear Material Detection in a Personnel Portal

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ABSTRACT

The concepts employed in the development of gamma-ray and neutron detection systems for a special nuclear materials booth portal monitor are described. The portal is designed for unattended use in detecting diversion by a technically sophisticated adversary and has possible application to International Atomic Energy Agency safeguards of a fast critical assembly facility. Preliminary evaluation results are given and plans for further parameter studies are noted.

KEYWORDS: Portal monitors, SNM monitors, radiation detectors, neutron detectors, IAEA safeguards, ZPPR

INTRODUCTION

The work described here is part of a joint Sandia Laboratories-Los Alamos Scientific Laboratory (LASL) effort to examine techniques for possible IAEA safeguards use at fast critical assembly (FCA) facilities and to develop and demonstrate components of an advanced containment and surveillance system. A study that examined methods for safeguarding fast critical facilities[1] identified containment of nuclear material by an unattended special nuclear material (SNM) portal monitor as a key element of the safeguards system. To meet that requirement, the monitor described here was developed by Sandia in consultation with LASL and has been described by Mangan.[2] Here, we intend to examine in depth the concepts used in the design of the neutron and gamma-ray detection system, and to indicate the results of the first steps in evaluation of the detection system performance, and to mention plans for further evaluation.

FIRST CONSIDERATIONS

The SNM inventory at a FCA facility includes plutonium of various isotopic contents and highly enriched uranium (HEU). The useful radiation characteristics of these two materials in an SNM monitor are quite different because plutonium fuel constituents emit both strong gamma-ray radiation and neutrons while uranium emits only rather soft gamma-ray radiation at a much lower specific activity. Further, examination of the unreflected

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[1] D. O. Gunderson and J. L. Todd, "International Safeguards for Fast Critical Facilities," Sandia Laboratories report, SAND 78-0168 (1978).

[2] D. L. Mangan, "A Personnel Portal for International Research Facility Safeguards," Nuclear Materials Management VIII, Proceedings Issue, 674 (1979).

critical masses[3] indicates that the critical mass of HEU is more than three times that of plutonium. Thus, more material must be diverted to achieve the same effect with uranium. Table I shows the specific intensity of penetrating radiation emitted by the major components of FCA fuel that are useful in detecting the presence of the fuel in a monitor. The first isotope, ^{235}U, is the principal component of the uranium fuel (93%) and the rest of the table entries are found in the plutonium fuel.

TABLE 1

MAJOR GAMMA-RAY AND NEUTRON SIGNATURES[4] OF FCA FUEL COMPONENTS

Isotope	Energy (KeV)	Intensity gammas/g/s	Comment
^{235}U	185.7	4.3×10^4	Only intense gamma ray easily attenuated.
^{238}U	1001.1	1.0×10^2	Arise from ^{234m}Pa daughter of ^{238}U.
	766.4	3.9×10^1	
^{239}Pu	413.69	3.4×10^4	
	129.28	1.4×10^5	
^{240}Pu	SF neutrons	1.0×10^3	
^{241}Am	59.5	4.6×10^{10}	Strong, but easily attenuated.

Table II shows the characteristics of some plutonium fuel at the Zero Power Plutonium Reactor (ZPPR), Argonne-West, Idaho, which is being used as a model facility for design purposes in development of the portal described here. The ZPPR fuel is all in the form of a plutonium-aluminum or plutonium-uranium alloy, an advantage for detecting diversion. In one case aluminum dilutes the plutonium, decreasing the self absorption of gamma-ray radiation in the fuel and augmenting the spontaneous fission (SF) neutrons with (alpha,n) reaction neutrons while, in the other case, ^{238}U adds some amount of penetrating gamma-ray radiation to the fuel. The trend shown in the final column of Table II results from the ^{241}Pu that decays to ^{241}Am. The amount of the latter closely follows the ^{240}Pu content listed, but there is an additional variation with the age of the fuel because the amount of ^{241}Am builds up with time. Other sources of possibly useful radiation that have been considered for detection of SNM, such as fission products[5] or ^{232}Th daughters in enriched uranium,[6] have not been found in large quantity in samples of fuel examined as part of this investigation[7], but could still be of importance for heavily shielded fuel because they emit more penetrating radiation.

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[3] W. R. Stratton, "Criticality Data and Factors Affecting Criticality of Single Homogenous Units," Los Alamos Scientific Laboratory report. LA-3612 (1967).

[4] R. H. Augustson and T. D. Reilly, "Fundamentals of Passive Nondestructive Assay of Fissionable Material," Los Alamos Scientific Laboratory report, LA-5651-M (1974).

[5] Tsahi Gozani, "Evaluation of Portal Monitors for the Detection of Nuclear Materials," Nuclear Materials Management VIII, Proceedings issue, 28 (1979).

[6] P. E. Fehlau and W. H. Chambers, "Perimeter Safeguards Techniques for Uranium Enrichment Plants," to be published.

[7] Hsiao-Hua Hsu, Los Alamos Scientific Laboratory, unpublished data. 1979.

TABLE II

ZPPR MAJOR FUEL TYPE CHARACTERISTICS

Manufacturer's Type	Components	Mass % Pu-U	Atom % ^{240}Pu	n/s/in[8]	Relative[8] Emission of ^{239}Pu γ/in	Relative[8] Emission of ^{241}Am γ/in
PAFI	Pu-Al	95	4.50	2,630	1.26	0.42
PUMS	Pu-U-Mo	20-78	8.66	1,730	0.67	0.49
PUMD & PUMN	Pu-U-Mo	28-69	11.6	3,000	1.0	1.0
PAHN	Pu-Al	97	22.3	11,600	0.96	3.44
PUMH	Pu-U-Mo	34-63	26.4	10,000	0.95	4.47

The nature of the plutonium fuel with its intense penetrating gamma-ray emitters is readily detected with conventional gamma-ray detectors when it is bare--i.e., not shielded--or when it is lightly shielded. Heavy gamma-ray shielding could hide the plutonium from a conventional gamma-ray detection so there is good reason to try to use the more difficult-to-shield neutron emission. Of course, it also makes sense to try to detect the presence of shielding material and Lopez[9] has described the system used in this portal. We pursued the neutron detection approach in addition to the detection of shielding in order to prevent passage of material that may be shielded with a more sophisticated gamma-ray attenuator made of a material such as lead dispersed in polyethylene. Dispersed small particle shielding is difficult to detect with metal detectors, but is a standard commercial item[10] and readily available. So, for plutonium there are good reasons for monitoring for both gamma-ray and neutron radiation in the context of safeguards where the adversary is technically competent and the monitor is unattended.

The uranium fuel is more difficult to safeguard because the intensity of the emitted gamma-ray radiation is lower than in the plutonium fuel and also, the gamma-ray radiation is all relatively soft and easily shielded. There is no useful neutron signature so the only alternate means to detect diversion is to detect shielding material. Our approach includes metal detection, as mentioned, and the use of the optimum detector for the detection of shielded uranium,[11] a plastic scintillator. Additional measures involving the detection of a decrease in gamma-ray and neutron backgrounds may be useful for detecting shielding and we intend to examine this concept during an upcoming evaluation period. A

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[8] J. T. Caldwell, Los Alamos Scientific Laboratory, unpublished data, 1978. The unusual unit of length used here, the inch, has become the unit of length in fuel plate sizes and they are found in sizes 1 through 8 inches. The inch is 2.54 cm long. The source strength for a particular fuel plate is obtained from the product of the tabulated numbers and the fuel plate length in inches.

[9] A. A. Lopez, "Shielding (Metal) Detector Development Program," Sandia Laboratories report, SAND 78-1969 (1979).

[10] Reactor Experiments, Inc., "General Catalog," 963 Terminal Way, San Carlos, CA 94070 is one supplier, but there are certainly others.

[11] P. E. Fehlau and E. R. Shunk, "UF_6 Gamma-Ray Measurements for SNM Portal Monitor Application," to be published.

[12] C. N. Henry and J. C. Pratt, "A New Containment and Surveillance Portal Monitor Data Analysis Method," 1st Annual ESARDA Symposium on Safeguards and Nuclear Materials Management, Proceedings, ESARDA 10, p. 126 (1979).

second technique, described by Henry and Pratt,[12] that we believe may extend the effectiveness of the booth for detecting a protracted diversion. This approach saves a net count for each occupancy and summation of data from many passages can achieve increased sensitivity.

DESIGN CONSTRAINTS

Instrumentation for containment and surveillance in international safeguards must function unattended, supported only by occasional visits from an inspector. Unattended operation translates directly to the requirement that a portal monitor, by its design and without human intervention, successfully deter diversion of nuclear material by any subterfuge available to an adversary short of physical destruction of the portal. Our choice of the booth configuration over the simpler walk-through designs commonly used in domestic safeguards was necessary to prevent several postulated defeat techniques, including the simple expedient of throwing material through the detectors too rapidly for detection. The most basic of design features--the use of separate detectors for metal, gamma-rays, and neutrons--resulted directly from the knowledge that an adversary can use large amounts of shielding to attempt to conceal material. Likewise, the arrangement of the gamma-ray detectors to eliminate regions of low sensitivity was dictated by the fact that an unobserved portal user is free to place or suspend material in any position in the portal volume where detection is least likely.

Integrating the three detector systems and the tamper-resistant features, with the often conflicting requirements of each, also imposed constraints on the design. For example, limited space available within the portal volume resulted in the combination of the lead background shielding and part of the polyethylene neutron moderator/reflector into one layer of lead-loaded polyethylene. The portal interior is another case. For the metal detector to function properly, the user had to be isolated by nonmetallic interior surfaces. These surfaces also had to be transparent to gamma-ray and neutron radiation, as well as have some tamper-indicating qualities. Walls, ceiling and floor fabricated of special boron-free fiberglass/epoxy with an overlay of Kevlar were used to simultaneously meet all these needs.

To minimize processing time per user, the gamma-ray, neutron, and metal detectors must operate simultaneously, but experiences with earlier versions of the portal indicated that cross-talk would be a problem. Electromagnetic shielding, careful routing of cables and wiring, and avoidance of current carrying loops partially solved these difficulties. However, to completely eliminate interference between the neutron and metal detector systems, we found it necessary in addition to actually interrupt both time and pulse counts in the neutron detector at the times when the metal detector shifts power from one transmit coil to the next.

Only occasionally did superposition of the three detector subsystems compromise the needs of one over another. Inclusion of background shielding in the doors could have caused sufficient flexure or position change to disrupt the metal detector, but omission of shielding from doors raises the background level inside the portal, which commensurately reduces gamma-ray detection sensitivity. Because the possible effect on the metal detector was worse, shielding was omitted from the doors.

THE GAMMA-RAY MONITOR

In order to avoid unnecessary development work, we chose to adapt commercially available SNM monitor components to our needs. Working together with a commercial manufacturer in a design study, we developed the system based on six large plastic slab scintillation detectors each of which is 3.8 cm thick and 160 cm by 20.8 cm in area. A second set of thicker detectors is also available for use in parameter studies. Placement of the detectors in the booth is illustrated in Fig. 1. Background is reduced by the 2.5-cm-thick lead loaded polyethylene covering the wall behind the detectors and the interior booth surfaces are designed to minimize attenuation of gamma-ray radiation. Detector signals are ganged and processed in a single signal-conditioning amplifier and single channel analyzer in our initial configuration. We anticipate possible advantages in grouping detectors into perhaps three separate groups and will examine this concept later.

The single channel analyzer (SCA) is used to define an energy window that we plan to set for optimum detection of shielded material. The basic approach used to optimize an energy window utilizes as a figure of merit the ratio S^2/B. Here, S is the net signal count in a convenient time interval and B is the experienced background count in the same interval. The ratio of S^2/B is used because we are searching for a signal S among statistical fluctuations that are sized proportionally to $\sqrt{B}$. Thus S^2/B clearly shows us when we have changed the detection sensitivity of a system. Examples of the utility of this approach are given by Fehlau.[13] In setting up the portal for initial operation, we have made measurements using a bare uranium source to determine appropriate system gain and SCA energy window.

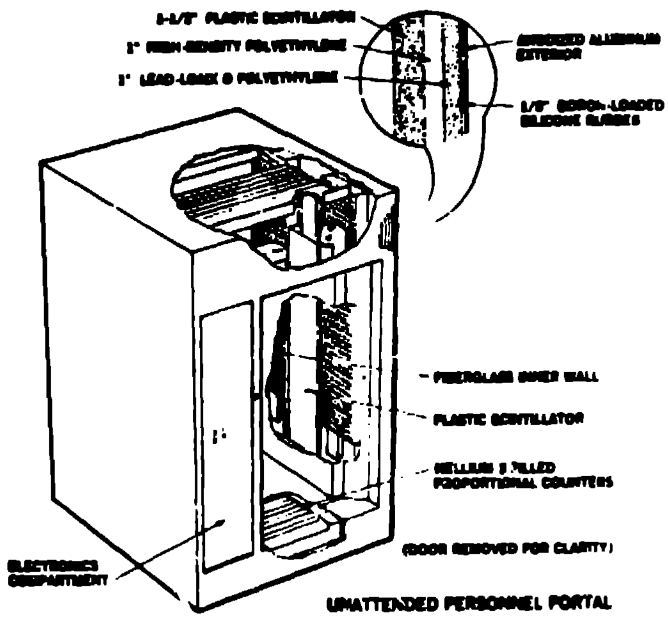

Fig. 1

The logic function for the gamma-ray system is based on a digital logic unit developed by a commercial manufacturer for possible application to domestic safeguards. The necessary logic unit modifications for this application were designed by Sandia who also carried out an extended debugging-development exercise on the software modifications to provide a workable unit. The basic logic approach is background following with a sliding interval signal algorithm[14] used to test against an alarm level derived from the background plus multiples of the standard deviation of the background. Many parameters of

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[13] P. E. Fehlau, et al., "On-Site Inspection Procedures for SNM Doorway Monitors, U. S. Nuclear Regulatory Commission report, NUREG/CR-0598 or Los Alamos Scientific Laboratory report, LA-7646 (1979).

[14] W. H. Chambers, et al., "Portal Monitor For Diversion Safeguards, Los Alamos Scientific Laboratory report, LA-5681 (1974).

the logic module are variable and final values await completion of the evaluation. Initially we use an alarm level of 4 standard deviations above the background and a 5 second count time. Other features of the logic module include the usual high limit alarm that prevents subversion by artificially raising background intensity and a low limit alarm to detect subversion or equipment failure. Command controlled LED's self-test the gamma-ray system by producing a pulse of light in each scintillator slab and an associated signal in the electronics.

Our preliminary testing of the gamma-ray system using the energy window for unshielded uranium consisted of static measurements rather than actual pass-through tests. We measured the response of the gamma-ray system to bare uranium samples and found that in the worst position in the booth, we should easily detect a compact 1 g sample of HEU in 2 seconds. This compares very well with domestic walk-through systems that use a 10 g sample for their procurement specification. Our initial measurements on shielded uranium fuel plates were done at the geometrical center of the booth, which is neither the highest nor the lowest sensitivity position. We found we could easily detect the smallest (72 g) HEU plate inside of a 5 cm thickness of lead loaded polyethylene that is equivalent to 1 cm of solid lead on a mass basis.

Preliminary testing with plutonium used a 1 inch size PANI fuel plate. This is the only fuel that has plates less than 2 inches long and, from the data of Table II, has the minimum gamma-ray and neutron intensity. At the central position we found that the 1 inch plate was easily detectable in 2 seconds inside of 5 cm of lead shielding that had a mass of 11 kg. An additional borated polyethylene shield with a mass of 32 kg for neutron shielding further reduced the gamma-ray signal, but it could be detected using a 3 second count.

For reference, these results were obtained in a gamma-ray background of 17 microR/h measured outside the portal. Inside, we measured 7 microR/h. We expect these reported sensitivities to change with background intensity as well as other variables such as shielding thickness and position of the source in the portal. We plan to publish more detailed results later.

THE NEUTRON MONITOR

The approach taken for neutron monitoring is novel and arises out of the development of a monitor for very large vehicles by Caldwell.[15] The unique feature is that the volume to be monitored is located inside a 4π solid angle neutron detector. This is achieved by including in the booth walls an almost continuous surface of polyethylene material that serves as neutron moderator and reflector. Neutrons born in the booth enter the moderator and some fraction of the neutrons are returned to the booth interior as thermal neutrons. These thermal neutrons may undergo several reflections before being lost by capture in polyethylene or in one of two arrays of ^{3}He proportional counters within the polyethylene cavity. Detector placement is not critical in the design and Fig. 1 shows our arrangement where twelve 5-cm-diameter by 90-cm-long ^{3}He tubes are in the floor and twelve in the ceiling. The total efficiency of this neutron detector has been calculated by Atwater.[16] We have verified his calculations by using PANI and PUMH ZPPR fuel plates in the otherwise empty booth and we measured a total efficiency value of 0.048. We used standard NIM proportional counter electronics and a logic system similar to the gamma-ray system.

Our initial evaluation was conducted at an altitude of 1676 m, so our natural background, from cosmic ray events, is near the maximum that will be experienced. We found that a background suppression of about 4% was caused by occupancy and our 43 kg

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[15] J. T. Caldwell, et al., "A Large Vehicle Portal Monitor for Perimeter Safeguards Application, 1st Annual ESARDA Symposium on Safeguards and Nuclear Material Management, Proceedings, ESARDA 10, p. 122 (1979).

[16] H. F. Atwater, Los Alamos Scientific Laboratory, unpublished data, 1978.

gamma-neutron shield caused an 8% reduction. The 32.5 g PANI plate in this shield was easily detectable and, in fact, we estimate that the total number of ^{3}He tubes may be reduced to perhaps as few as 4 from the present 24.

SUMMARY

To put this monitor in perspective, we point out that present practice in domestic safeguards utilizes rather inexpensive walk-through[14] or hand-held[17] monitors that detect gamma-ray radiation. Great reliance is placed on the inspector in attendance to properly operate the monitors and prevent unusual behavior by those being monitored. In contrast, the booth monitor we have described is a stand alone instrument capable of detecting gamma-ray radiation, neutron radiation, and shielding in a manner that is difficult to subvert. It employs novel techniques for neutron detection and its gamma-ray system represents what we believe is an optimal detector for monitoring a booth size volume. The effort spent in development of the booth monitor by many individuals at Sandia and LASL has beneficial effects in developing expertise in the basic problems pertinent to SNM monitoring.

ACKNOWLEDGMENTS

The authors appreciate the efforts of the many individuals who participated in the design, construction, and testing of the SNM monitor described here. P. E. Fehlau would like to specifically thank two individuals at Sandia Laboratories who have been involved in bringing the passive detection system into being; Anthony E. Sill, who was responsible for the system logic and Donald J. Gould, who was responsible for the radiation detectors.

The work reported here was performed under the auspices of the U. S. Department of Energy.

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[14] W. H. Chambers, (1974).

[17] W. E. Kunz, "Portable Monitor for SNM," Los Alamos Scientific Laboratory informal report, LASL-77-18 (1977).