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Six-Inch-Square Phoswich Detector Array for Plutonium Lung Counting

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Two 6-in.- (15.2-cm-) square phoswich detectors obtained from the Harshaw Chemical Company have been evaluated for possible application as plutonium lung counters. Although our evaluation is still preliminary, the data collected to date suggest that the use of these detectors for routine lung counting would reduce the minimum detectable activity for isotopically pure ^{239}Pu by about 40%, such that a maximum permissible lung burden of pure ^{239}Pu (16 nCi) could be detected in a plutonium worker of average stature with 2.6-cm chest-wall thickness in a 4000-s count. At present, using two 11.4-cm-diam phoswich detectors, one lung burden of ^{239}Pu is not detectable in the same counting time. Our preliminary data also suggest a reduction in the Minimum Detectable Activity for ^{241}Am, even though the background count-rate for these detectors is much higher in the 60-keV band used for spectral analysis.

Introduction

At LLNL, the detection and measurement of plutonium in the lung is generally done using two 11.4-cm-diam phoswich detectors[1,2] placed high on the chest and tangent to the sternum and clavicle. The counts are made in a well-shielded environment using pulse-shape-discrimination electronics to reject Compton-scattered events and photomultiplier tube noise, thus achieving a detector background of approximately 4 cpm in the 17-keV band used for plutonium analysis. Adding this background to the subject's own background due to ^{40}K scatter in the body, etc., allows the calculation of Minimum Detectable Activity (MDA) values which can then be derived for people of differing body types.

One series of MDA calculations at the 95% confidence level is shown plotted in Fig. 1 for three common isotopically pure actinide elements. These cover a wide range of values depending upon the composition and chest-wall thickness of the subject and the detection efficiency of the counter for the particular radionuclide of interest.

All of the MDAs were calculated using a modified formula of Altshuler and Pasternak,[3] shown in Eq. (1), where the subject and detector background count-rates are not well known:

$$\mathrm{MDA} = 2K\frac{\left(2\frac{B}{T}\right)^{1/2} + \frac{K^2}{T}}{S} \qquad (1)$$

where K is the constant determined by the confidence level (1.645 for 95%), B is the background count-rate, T is the counting time (min), and S is the sensitivity (cpm/μCi), assuming a mean value of 22% fat and 78% muscle for all chest-wall thicknesses.[4]

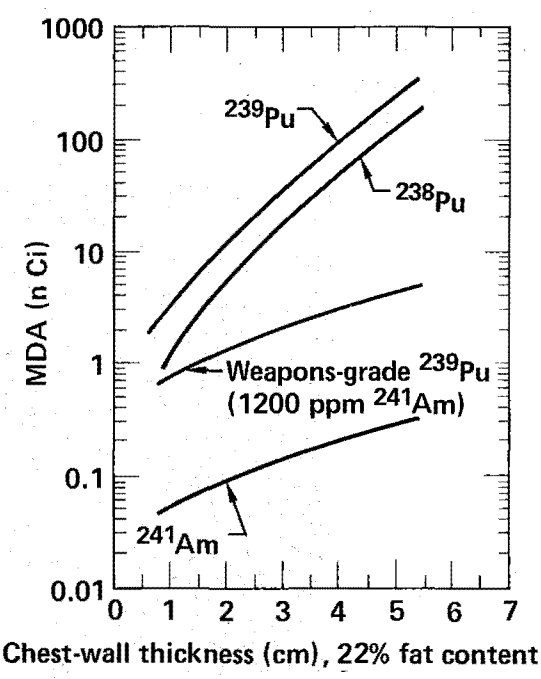

Figure 1. MDA calculations for ^{239}Pu, ^{238}Pu, and ^{241}Am, based on counts taken with the 11.4-cm-diam detector.

A more rigorous statistical analysis using actual observed human background variability, etc., incorporating the methods proposed by Faulk and Coop,[5,6] might be more appropriate in describing these MDA values; however, for the present we are using the plotted values as a relative basis for comparing the MDAs calculated for a second detection system which will be discussed later.

For ^{241}Am, the MDA is comparatively low, less than 0.3 nCi for all of the subjects, compared with a maximum permissible lung burden of 15 nCi. For ^{238}Pu, with a maximum permissible lung burden of 16 nCi, the MDA varies from about 6 to 30 nCi over a range in chest-wall thickness from 2 to 3.5 cm, accommodating most individual body types. For ^{239}Pu, the MDA varies from about 12 to 60 nCi over the same range, showing that one maximum permissible lung burden of 16 nCi is not detectable in a person of average stature with a 2.6-cm chest-wall thickness.

However, if it is known that the plutonium mixture is weapons-grade material, with say 1200 ppm ^{241}Am content, and americium can be used as a tag in the measurement, then the MDA values for plutonium range from about 1 to 3 nCi.

Large-Area Square Phoswich Detectors

In October 1980, two 6-in.- (15.2-cm-) square phoswich detectors became available to our laboratory for possible application as plutonium lung counters. Each detector consists of a 0.5-in.-thick sodium iodide crystal, backed by a 1.5-in.-thick cesium iodide crystal (NaI activated), both of which are coupled to the same 5-in.-diam photomultiplier tube. The entrance window is 10-mil beryllium, with associated electronics similar to that used for the 11.4-cm-diam phoswich detectors.

Background Count-Rate and Energy Resolution

The detectors have a remarkably low background count-rate for their size. There are only about 5–6 cpm in the plutonium x-ray band summed from 13 to 24 keV, compared with 4 cpm for the two 11.4-cm-diam detectors, even though the square phoswich surface area is 2.3 times greater. From 50 to 70 keV, the background count-rate is approximately 17 cpm compared with about 10 cpm for the 11.4-cm-diam detectors. The square phoswich also has a better energy resolution. Figure 2 shows a ^{241}Am spectrum taken with both systems. The superior resolution reflects the good light-collection capability of the 15.2-cm-square detector compared with the 11.4-cm-diam detectors. However, this may not be a fair comparison, since the 11.4-cm-diam detectors are old and are probably in need of re-work at the factory. Some of the newer 5-in.- (12.7-cm-) diam detectors exhibit good resolution characteristics when compared with the square phoswich.

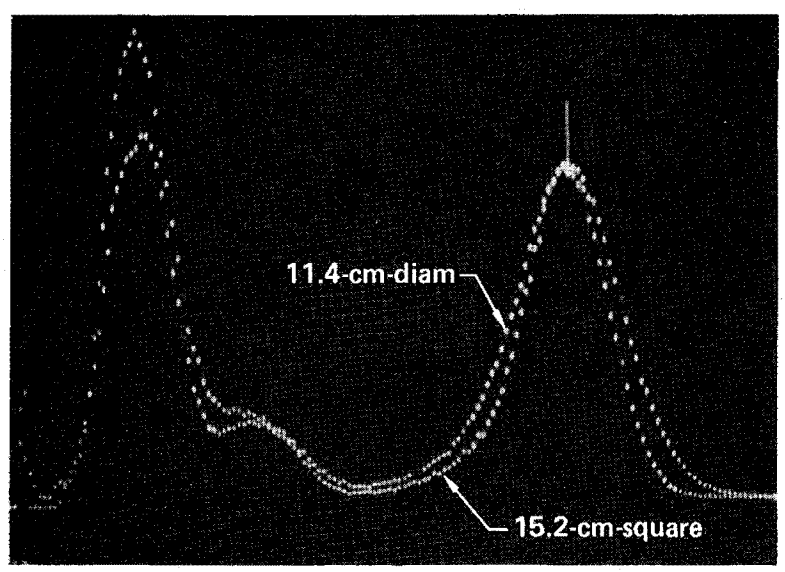

Figure 2. ^{241}Am spectrum taken with the 15.2-cm-square and 11.4-cm-diam detectors.

Measurement Comparisons

Calibration data taken using the LLNL Realistic Phantom[7,8] and compared in Figs. 3 and 4 for ^{239}Pu and ^{241}Am in lungs show that counting efficiencies are about a factor of two greater for the 15.2-cm-square detector.

MDA calculations similar to those derived for the smaller detector are compared in Fig. 5 for the square detector. They suggest that the use of these detectors for routine lung counting would reduce the MDA for isotopically pure ^{239}Pu by about 40% relative to the 11.4-cm-diam detector, such that a maximum permissible lung burden of pure ^{239}Pu (16 nCi) could be detected in a plutonium worker of average stature with a 2.6-cm chest-wall thickness in a 4000-s count. The data also suggest a theoretical reduction of about 30% in the MDA for ^{241}Am.

To test the validity of these calculations, phantom measurements were made using mock lungs containing 16.4 nCi of uniformly distributed ^{239}Pu or about one lung burden of activity. Measurements of an inactive phantom with 2.63-cm chest-wall thickness and 18% fat content were subtracted from the measurements of the active phantom. A total of three measurements were made and in each case the residual counts were positive in the 17-keV band. Two additional

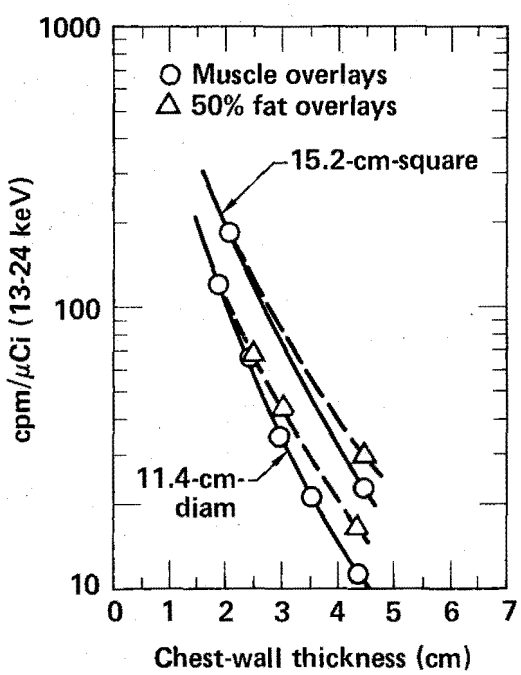

Figure 3. Counting efficiencies of the two detectors for ^{239}Pu.

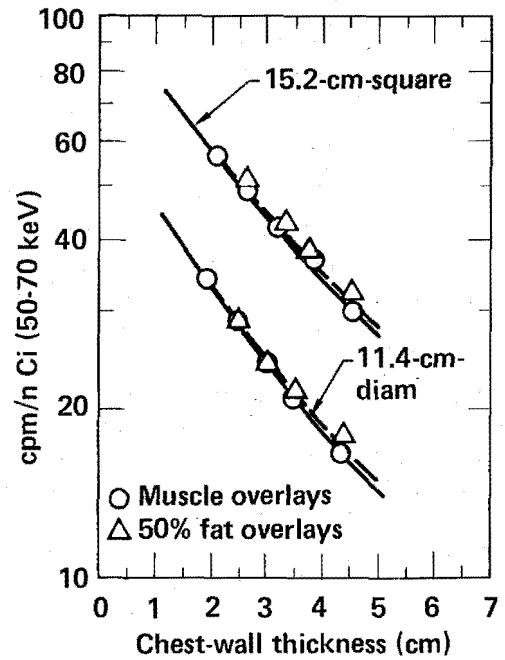

Figure 4. Counting efficiencies of the two detectors for ^{241}Am.

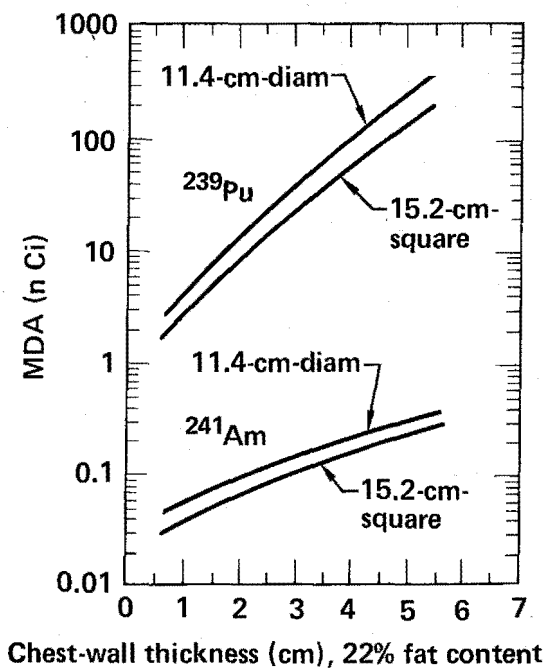

Figure 5. MDA calculations for ^{239}Pu and ^{241}Am, based on counts taken with the two detectors.

counts, made for 6000 s, were also positive. One phantom count made with a 2.08-cm chest-wall thickness and 0% equivalent fat content was detectable, while a second count made using a 3.16-cm chest-wall thickness equivalent to a 17% fat content was not detectable.

Lungs loaded with a mixture of 2 nCi ^{241}Am and 32 nCi ^{239}Pu to simulate weapons-grade material with 1200 ppm ^{241}Am weight fraction were also measured, but not under the same conditions as for the 16-nCi lungs. In general, plutonium will be more difficult to detect in this situation, since the x rays from both plutonium and americium will be riding on top of a continuum from the scattered 60-keV gamma rays from ^{241}Am. However, after stripping out the x-ray contribution from americium, 32 nCi of ^{239}Pu activity was still detectable in the phantom for chest-wall thicknesses of 2.08 cm and 2.64 cm and 0% fat content, but not at the next thickest phantom chest overlay, 3.16 cm. One detector became damaged and had to be returned to the factory before additional measurements using chest plates and torso equivalent to a 22% fat content could be made.

No low-level ^{241}Am measurements were made on the phantom before the detector became damaged. However, several measurements using similar counting geometries had been made on people with small amounts of ^{241}Am present. The results of some of these counts are shown in Fig. 6. The upper curve shows a small subject (A) with 0.3 nCi ^{241}Am in the lung, compared with a large subject (B) of 3.6-cm chest-wall thickness with about 0.2 nCi. A normal (no ^{241}Am) subject (C) of equivalent size to the large subject is shown in the third curve. The bottom curve is subject (B) counted with the 11.4-cm-diam phoswich array. All of these counts were made for 3000 s, with the 60-keV gamma ray used for analysis.

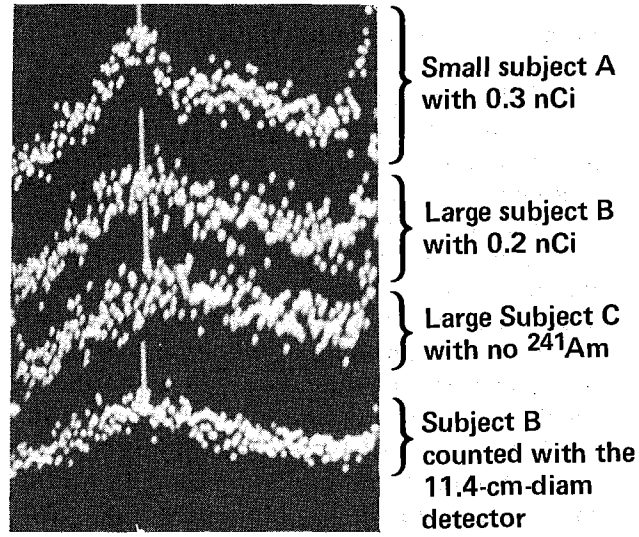

Figure 6. ^{241}Am spectra taken with the 15.2-cm-square detector.

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