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IN VIVO MEASUREMENT OF ACTINIDES IN THE HUMAN LUNG

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ABSTRACT

The problems associated with the *in vivo* detection and measurement of actinides in the human lung are discussed together with various measurement systems currently in use. In particular, the methods and calibration procedures employed at the Lawrence Livermore Laboratory, namely, the use of twin Phoswich detectors and a new, more realistic, tissue-equivalent phantom, are described. Methods for the measurement of chest-wall thickness, fat content, and normal human background counts are also discussed. Detection-efficiency values and minimum detectable activity estimates are given for three common actinides, ^{238}Pu, ^{239}Pu, and ^{241}Am.

DISCLAIMER

INTRODUCTION

Of all the actinides, isotopically pure ^{239}Pu is probably the most difficult to detect and measure in the human lung. Several problems are associated with its measurement.

- The maximum permissible lung burden is low, only 16 nCi.
- Even though ^{239}Pu has over 100 different nuclear transformations, none of the high-energy gamma lines occur with enough intensity to make it practical to count them, and there are essentially no K x rays.
- Only the uranium L x rays accompanying the alpha-decay process are abundant enough for counting and these are not very intense, only about 4.6% per disintegration. Because of their low energy (17 keV), they are heavily attenuated in bone and tissue so that very few x rays emerge from the body surface and are available for counting. For one maximum permissible lung burden, only about one x ray per minute can be detected.
- There are also uncertainties in the composition and thickness of overlying tissue, each 1-mm error producing about a 12% error in calibration factor.
- Finally, the deposition pattern in the lung is usually not known, although most laboratories assume uniformity.

Many of the same problems are associated with measurement of some of the other actinides but to a lesser degree. A few (such as ^{241}Am and ^{235}U, both of which have intense high-energy gamma lines) are comparatively easy to detect. It is even possible to measure ^{239}Pu

more reliably, if the isotopic composition of the plutonium mixture is known, by using ^{241}Am as a tag in the measurement. However, this method is only reliable for new exposures and is usually not useful for older exposures where the americium with time may have translocated differently in the body compared with plutonium.

DETECTION SYSTEMS

The detection systems employed for the measurement of these nuclides are about as varied as the number of laboratories making the measurements. However, they generally fall into three catagories:

First, for low-energy photons, the Phoswich detector (LA_a68, LA_b68) is perhaps the most widely used, either as a single detector placed centrally over the chest or, as shown in Fig. 1 for the Lawrence Livermore Laboratory (LLL) system, with two 11.4-cm-diam detectors placed high on the chest and tangent to the sternum and clavicle.

Next are the large-area proportional counters (RA69), which view a larger portion of the chest and offer less geometry dependence and better resolution but poorer efficiency than the Phoswich detector at high energy.

A few laboratories now use intrinsic germanium planar arrays (FA78, GO79). These systems have extremely good resolution but are very expensive.

CALIBRATION PROCEDURES AND ASSOCIATED ERRORS

An accurate calibration of the counting system is essential for the proper assessment of any internal depositon in the lung. Until recently, an Alderson-Remab* phantom was used for calibration purposes at LLL and at a few other laboratories. This phantom (see Fig. 2) is a commercially available take-apart phantom having a human skeleton and fillable compartments to simulate the body organs, including lungs. The phantom, although entirely adequate for many purposes for which it was intended, has proved deficient as a calibration medium for counting plutonium in lungs.

The Alderson-Remab phantom has now been replaced by a more realistic torso phantom (DE76, GR78) constructed at LLL under sponsorship of the U.S. Department of Energy Intercalibration Committee for Low-Energy Photon Measurements (a seven-laboratory committee who developed the criteria for the phantom construction). The phantom simulates a human male torso without head or arms and is terminated just above the pelvis. Its dimensions are based on the anatomical average of 500 employees of Los Alamos Scientific Laboratory and LLL. The torso includes a human male rib cage and is made of solid tissue-equivalent material that closely matches the photon-attenuation properties of human tissues at energies down to 15 keV.

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*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

The phantom has removable major organs, including the lungs and lymph nodes. It also has chest plates of tissue-equivalent material that can be overlaid on the phantom's basic core to simulate a range of chest-wall thicknesses from 1.9 to 4.3 cm. The phantom has two sets of overlay plates to simulate tissue attenuation by lean muscle or by a combination of adipose and muscle (50% of each by weight).

Figure 3a shows the completed phantom torso, which is made of muscle-equivalent material with a 1.9-cm-thick chest wall.

Figure 3b shows one of the overlays in place to simulate a thicker chest wall. Two 5-inch diam circles are marked on the overlay for detector placement (although detectors may be placed in other locations if desired).

A view of the human skeleton incorporated into the phantom is shown in Fig. 3c, with cartilage-equivalent material connecting the ribs and sternum.

The lungs are molded as shown in Fig. 3d, with the nuclide of interest incorporated into the lung material. The first of three phantoms has been completed, and we now have lung sets for highly pure ^{238}Pu, ^{239}Pu, ^{241}Am, and natural uranium. Additional sets are planned for curium and various isotopic mixtures of uranium.

Figure 3e indicates the placement of the lungs and other organs in the body cavity. The heart, liver, and kidneys are encased in a tissue-equivalent filler material.

For calibration purposes, counts on the phantom are made with the detectors placed on the chest as shown in Fig. 1 and both with and without the two sets of chest plates in order to develop calibration curves for the counter for each nuclide of interest. At the present time, four laboratories have completed their initial measurements on the phantom, and measurements at a fifth laboratory are now in progress. In early 1980, all of the calibration data from each of the laboratories will be analyzed and compared and will be the subject of a separate report by the committee.

Initial detection-efficiency measurements for ^{238}Pu made on the phantom at LLL are shown in Fig. 4a. Note that the efficiency of the counter changes rapidly with small changes in chest-wall thickness, making accurate measurements of the chest wall a necessity. The last point, at 4.3 cm, in the upper curve represents a person with about 30% fat content. Therefore, for low-energy x rays, the subject's fat content must also be assessed. This is not so important when measuring high-energy gamma rays. For example, the changes in detection efficiency for ^{241}Am are much less dependent on the amount of fat present and can be largely ignored (see Fig. 4b).

Chest-wall thickness is measured at most laboratories by using A-mode ultrasonic techniques with a single transducer, as shown in Fig. 5. In this method, individual measurements of six to nine separate points are made within an area viewed by the detectors on each side of the chest, and the points are averaged exponentially to obtain an average chest-wall thickness for the total area. The interpretation of the single-point measurements, however, has been found in practice to be very difficult and misleading.

At LLL a different method is used that involves a compound-arm B-scanning system (CA73, CA76) (Fig. 6a). Continuous transverse and sagital scans are traced over an area covered by the detectors and on each side of the chest along the lines indicated in Fig. 6b. These correspond to vertical scans at 30, 60, 90 and 120 mm on each side of the body midline and to transverse scans through the center and at ± 40 mm.

The scans are recorded on magnetic tape and processed in a computer system that displays each scan in 64 colors, depending upon echo intensity. Points are then marked on the scan to define the chest surface and the lung interface. Then an equation is derived for the points by using a spline fit.

An additional computer program then selects points along the chest surface and at the lung interface to calculate the minimum between each set of points. Approximately 80 points from all of the scans are then averaged exponentially to give the average chest-wall thickness.

The computer is also capable of calculating the fat content by an operator-assisted graphic-analysis technique. One such scan made at 60 mm to the left of the body midline is shown in Fig. 7. The chest surface and the lung interface are indicated by the arrows. The position of the ribs is shown clearly, along with a layer of fat between the chest surface and the lung.

One advantage of the B-scan ultrasonic system is that a cross-sectional view of the area being scanned, with all of the anatomical boundaries of interest, can be displayed immediately on a storage scope. This is of immense value in the interpretation of the sonic data.

A number of x-ray transmission measurements have been made at LLL by using the new phantom with a combination of overlays to determine the effect of fat content on detection efficiency of the lung counter (CA78). In Fig. 8, the change in detection efficiency for plutonium x rays is plotted as a function of fat content.

According to one study (DO73), the fat content in the human chest wall varies from 10 to 34%, the mean value being 22%. This represents about a 30 to 40% change in lung counter-calibration factor for plutonium x rays passing through the 2.8-cm-thick chest wall (the average for an LLL worker). Since the total correction for extremes in body build could exceed 70% or more, this is obviously an important variable that should be determined when measuring plutonium deposition in the lungs.

Wedges of intercostal tissue (see Fig. 9) removed from the chest of a male cadaver indicate the extent to which fat can accumulate in the chest wall. In this case, the fat content was about 60%.

Another problem in lung counting is the determination of the normal background count for the human subject being counted. Some laboratories account for this background by subtracting a "clean-person" match from the net spectrum of the subject. This method has also been used at LLL. However, more recently at LLL, the clean-person background is estimated by integrating a portion of the subject's own spectrum in a high-energy band (80 to 100 keV) and then using this value to calculate the normal background in the plutonium band at low-energy (13 to 24 keV), using the relationship established in Fig. 10a for 62 "clean" individuals of varying body type. Estimates can be determined in the same way to predict the normal background in the ^{241}Am band from 50 to 70 keV, using the data given in Fig. 10b, for the same 62 clean individuals. However, both of these estimates can only be made to about ±30% accuracy.

The uncertainty in the distribution pattern for the lung of the person being counted is probably one of the largest single sources of error in establishing a proper calibration factor for the lung count. This can vary widely depending upon the subject's breathing pattern and lung physiology. From the work of Newton, et al. (NE72), it is known that these errors can approach at least 70%.

MINIMUM DETECTABLE ACTIVITY (MDA)

At Livermore, we now use the new more realistic phantom calibration, and since the subject's background count is usually not well known, we calculate MDA at the 95% confidence level from a modified formula of Altshuler and Pasternak (AL63) (shown in Eq. 1). In this case, the background is assumed to be the detector background plus the estimated clean-person background for the energy band of interest.

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

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). The MDA plots are shown in Fig. 11 for three common actinide elements.

The MDA, as calculated from Eq. 1 for a 4000-s count, covers a range of values that depend on the chest-wall thickness of the subject and the sensitivity of the counter for the particular radionuclide of interest. Deposition in the lung is assumed to be uniform.

For ^{241}Am, the MDA is comparatively low, less than 0.3 nCi for all of the subjects, compared with the maximum permissible lung burden of 15 nCi.

For ^{238}Pu, where the maximum permissible lung burden is 16 nCi, the MDA varies from about 7 to 30 nCi over the chest-wall-thickness range from 2 to 3.5 cm (the large majority of people fall within this range).

For ^{239}Pu, the MDA varies from about 16 to 60 nCi over the same range.

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

ACKNOWLEDGMENT

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FIGURE CAPTIONS

Fig. 1. Use of Phoswich detector at LLL for plutonium counts of lungs.

Fig. 2. Alderson-Remab calibration phantom showing plutonium-loaded lungs.

Fig. 3. The LLL calibration phantom No. 1. (a) Completed torso. (b) Torso with 11-mm overlay plates. (c) Organ-cavity cast with rib cage in place. (d) Lung and mold used for casting. (e) Torso with chest cover removed to show organs.

Fig. 4. Detection efficiency for actinides in lungs of LLL phantom No. 1. (a) ^{238}Pu and ^{239}Pu. (b) ^{241}Am.

Fig. 5. A-mode ultrasonic system for measurement of chest-wall thickness.

Fig. 6. B-scan ultrasonic system. (a) Compound arm used for measurement of chest-wall thickess. (b) Schematic of chest area, showing where B scans are made.

Fig. 7. B scan of the chest of LLL phantom taken 60 mm to the left of the body midline.

Fig. 8. Percent change in detection efficiency as a function of fat content in the chest wall (LLL phantom No. 1 used).

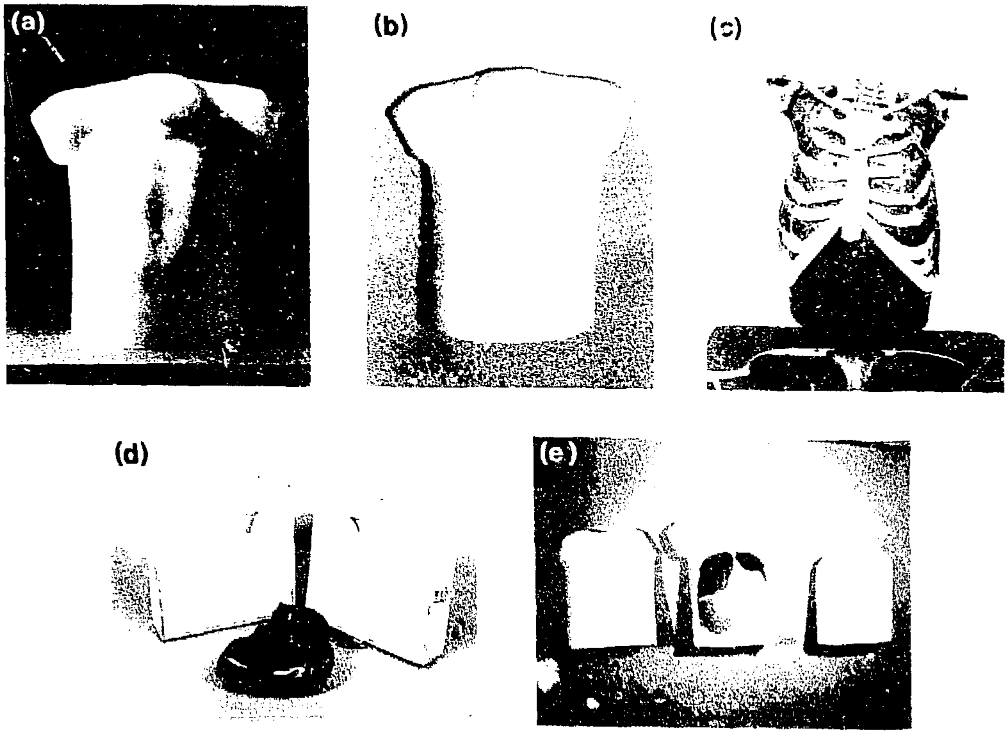
Fig. 9. Wedges of intercostal tissue removed from chest of a male cadaver.

Fig. 10. Estimates of background counts on humans (see text). (a) For plutonium band at 13 to 24 keV versus counts at 80 to 100 keV. (b) For americium band at 50 to 70 keV versus counts at 80 to 100 KeV (r is the coefficient of linear correlation).

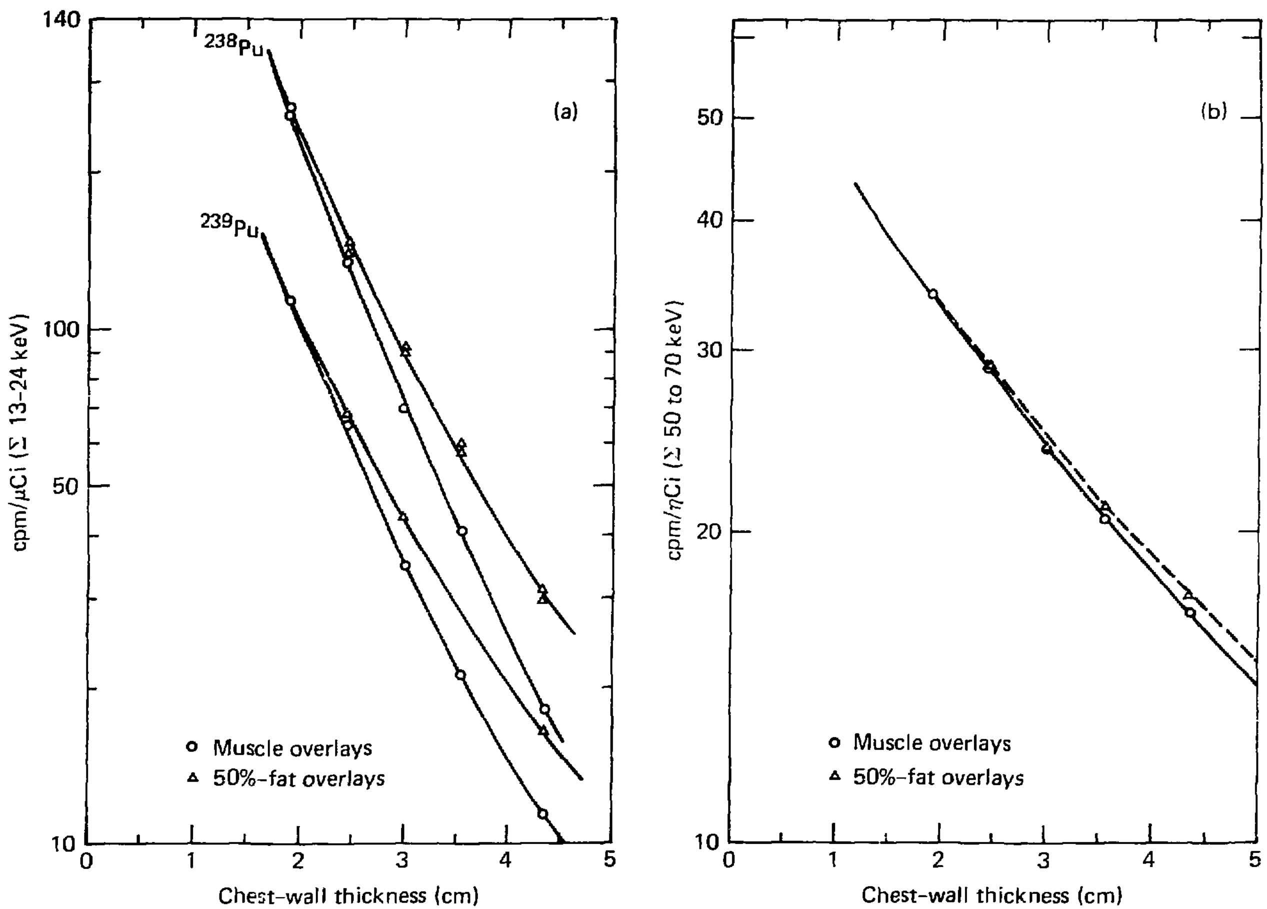
Fig. 11. Minimum detectable activity (MDA) as a function of chest-wall thickness. The LLL phantom No. 1 and twin Phoswich lung counter were used (4000-s count; 95% confidence level).

ANDERSON - Fig. 1

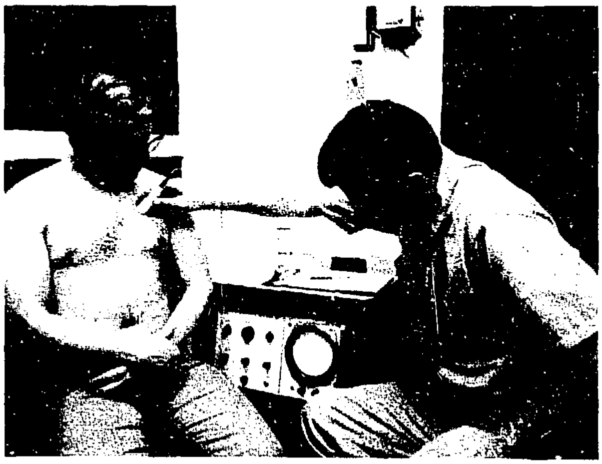
ANDERSON - Fig. 2



ANDERSON - Fig. 3

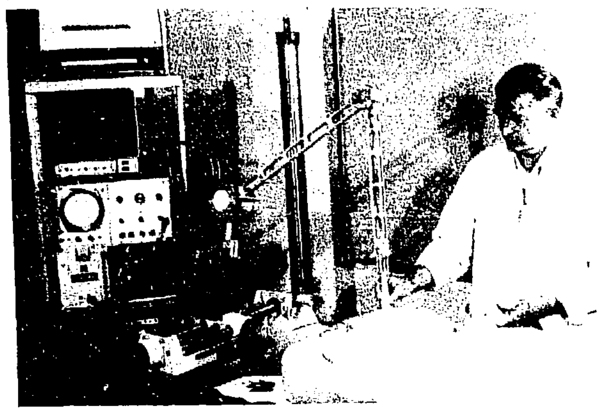


ANDERSON - Fig. 4



ANDERSON - Fig. 5

(a)



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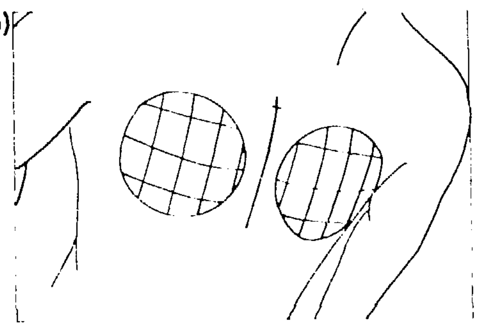

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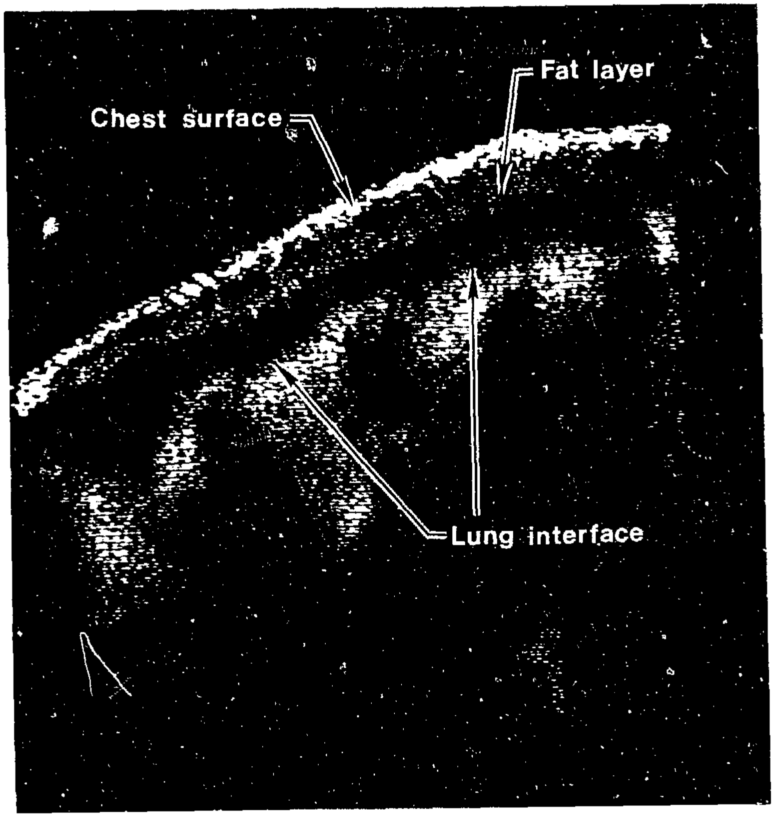
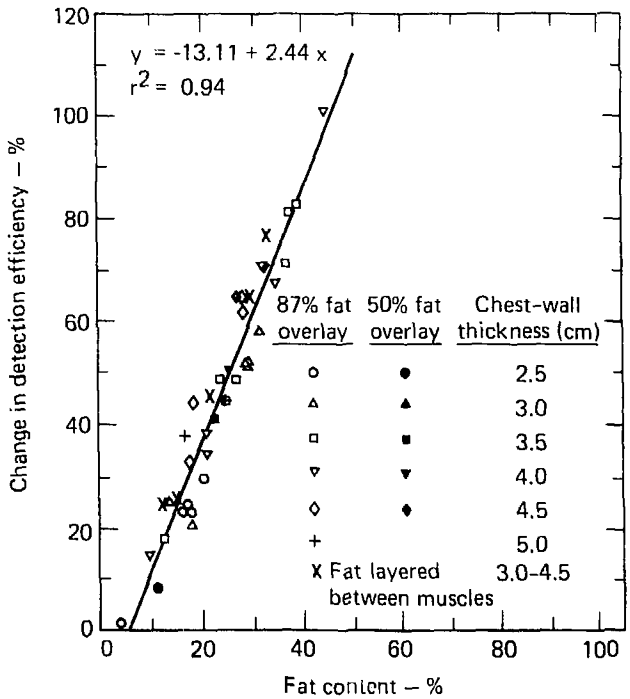
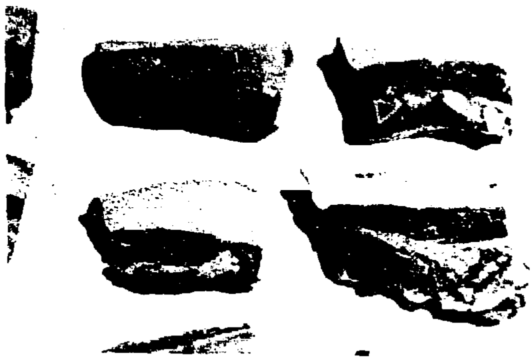


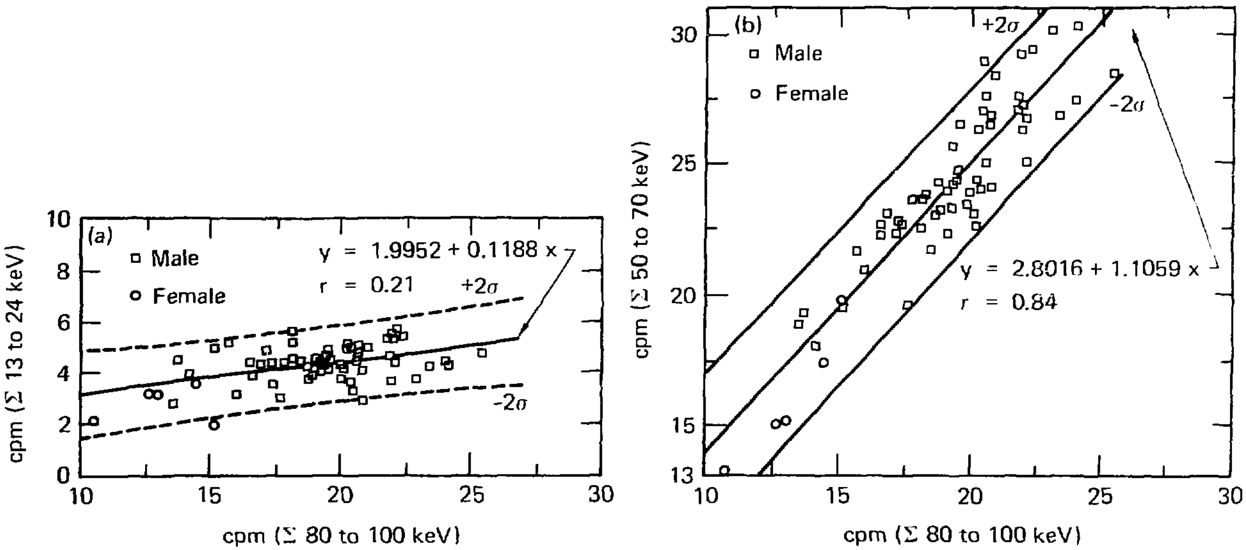
ANDERSON - Fig. 7



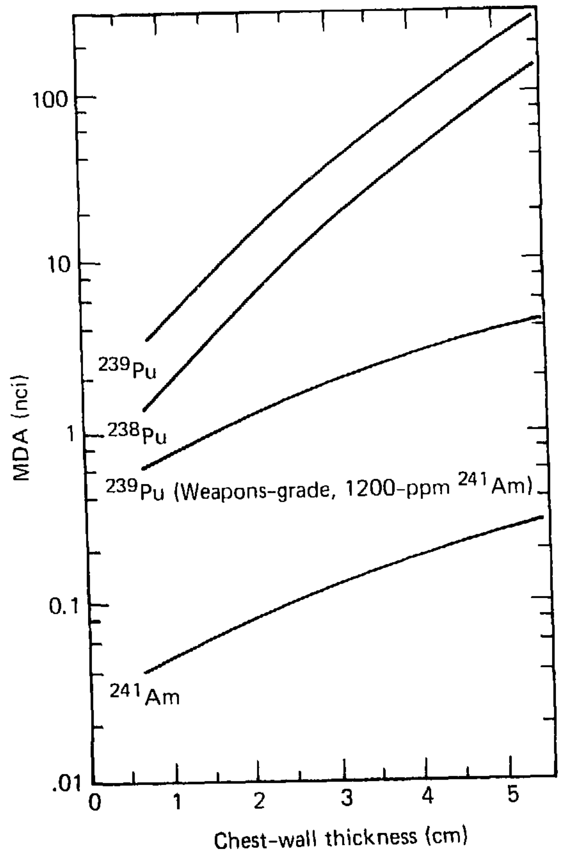
ANDERSON - Fig. 8



ANDERSON - Fig. 9



ANDERSON - Fig. 10



ANDERSON - Fig. 11