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# TISSUE-EQUIVALENT TORSO PHANTOM FOR CALIBRATION OF TRANSURANIC-NUCLIDE COUNTING FACILITIES

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## ABSTRACT

Several tissue-equivalent human-torso phantoms have been constructed for the calibration of counting systems used for in-vivo measurement of transuranic radionuclides. The phantoms contain a simulated human rib cage (in some cases, real bone) and removable model organs, and they include tissue-equivalent chest plates that can be placed over the torso to simulate people with a wide range of statures. The organs included are the lungs, liver, and tracheobronchial lymph nodes. Polyurethane with varying concentrations of added calcium was used to simulate the linear photon-attenuation properties of various human tissues, including lean muscle, adipose-muscle mixtures, cartilage, and bone. Foamed polyurethane was used to simulate lung tissue. Organs have been loaded with highly pure $^{238}Pu$, $^{239}Pu$, $^{241}Am$, and other radionuclides of interest. The validity of the phantom as a calibration standard has been checked in separate intercomparison studies using human subjects whose lungs contained a plutonium simulant. The resulting phantom calibration factors generally compared to within ±20% of the average calibration factors obtained for the human subjects.

## INTRODUCTION

One of the most difficult problems in health physics is the accurate and sensitive in-vivo measurement of $^{239}Pu$ and other transuranic radionuclides in the human body. Low photon-emission rates, absorption of the low-energy photons by bone and soft tissue, uncertainties in the estimate of internal deposition patterns, and low permissible organ burden (for example, 16 nCi of $^{239}Pu$ in the lung) make detection and quantification of transuranics at health-protection levels difficult.

An important aspect of accurate in-vivo assay is the need for a realistic calibration phantom that (1) reproducibly simulates the counting geometry of internally deposited radionuclides, (2) is made of materials that simulate the photon-attenuation properties of human tissue (muscle, bone, adipose, cartilage, liver, and lung) at energies below 20 keV, and (3) is rugged enough for use in routine laboratory and interlaboratory calibration programs.

The first three such phantoms were completed at Lawrence Livermore National Laboratory (LLNL) [Griffith et al., 1978], using construction criteria specified by the U.S. Department of Energy Intercalibration Committee for Low-Energy Photon measurements (Dean et al., 1976). The committee, now disbanded, comprised whole-body-counting specialists from seven major national laboratories and DOE contractors. Each phantom simulates a human male torso, without head or arms, terminated just above the pelvis. Its dimensions (height, weight, and chest circumference) are based on the anatomical average of 500 typical radiation workers from Los Alamos National Laboratory and LLNL. The phantom consists of a tissue-equivalent (TE) polyurethane torso shell with an imbedded human-male rib cage. Removable TE lungs, heart, liver, and lymph nodes and additional TE material simulating intestines and body fluids fill the phantom cavity. Chest plates of TE material that overlay the phantom simulate the geometry and chest-wall attenuation of a range of statures seen in male radiation workers. Three sets of chest plates simulate tissue attenuation provided by lean muscle or by a combination of adipose and muscle (50% of each by weight, or 87% adipose and 13% muscle). Initially, TE kidneys were prepared for use with the phantom, but they were not used in the final construction.

A uniform deposition of isotopes in an individual organ can be simulated by labeling the TE organ with the appropriate materials. For example, several liver, lymph nodes, and lung sets have been labeled with high purity $^{238}$Pu, $^{239}$Pu, and $^{241}$Am. Although the phantom is designed principally for the calibration of transuranics, various isotopic mixtures of uranium, thorium, and other radionuclides of interest, including fission and activation products, have also been used.

Included behind the tracheobronchial plane of the phantom is a 1-cm-diameter channel to permit calibration with esophogeal detectors. Later models of the phantom produced and marketed by Humanoid Systems, Inc. of Carson, California omit the esphogeal channel and, in place of the real bone used in the original three phantoms, use bone-equivalent polyurethane to simulate the rib cage and other bones. The newer phantoms also have a coordinate grid pattern to facilitate measurement reproducibility; otherwise, the phantoms are identical.

## TISSUE-EQUIVALENT MATERIAL

Radiologists and whole-body-counting specialists have used a variety of tissue-equivalent materials to simulate human tissue. These include common, readily available materials, such as Lucite, Perspex, and polyethylene. However, when low-energy x rays are involved, the radiation attenuation properties of human tissue must be simulated more carefully. Even differences in attenuation between soft tissues such as muscle, adipose tissue, and cartilage become important. Consequently, other researchers have developed specific TE material formulations such as Mix-D (Jones, 1959), Temex (Stacey et al, 1961), and Rando muscle-equivalent material (manufactured by Alderson Research Laboratories, Stamford, Conneticut).

For various reasons, none of these materials were satisfactory for use in the phantom, mainly because of the need for tissue simulation at energies as low as 15 keV, for easy forming of the material into irregular shapes, for durability with minimum deformation over many years, and for varying the composition of the material to produce a family of different tissue simulants such as lung, adipose, muscle, cartilage, and bone to simulate real tissue densities from 0.26 to 1.27 g/cm$^3$. It was also necessary to uniformly label the TE materials with plutonium, americium, uranium, and other heavy elements.

Polyurethane was chosen as an appropriate basis for the above family of TE materials because it has attenuation properties that approximate those of human tissue with 87% adipose and 13% muscle. It also has a composition of 9.2% hydrogen, 68.9% carbon, 3.7% nitrogen, and 18.2% oxygen (by weight), and a density of 1.06 g/cm3. Denser tissues like cartilage, muscle, and bone can be simulated by adding small quantities of material with a higher atomic number, such as calcium. Polyurethane can easily be cast in irregular shapes, and commercial formulations are available to produce both solid and foamed polyurethane in the range of densities needed to simulate all of the phantom body parts, including the lung. Specific details of selected commercial and modified LLNL TE formulations are found elsewhere (Griffith et al., 1978).

We have measured the photon transmission characteristics of various animal tissues and TE materials using 16.6-keV x rays from $^{93m}$Nb, L-series x rays from $^{238}$Pu, and 60-keV gamma rays from $^{241}$Am. The transmission curves for $^{93m}$Nb and $^{238}$Pu, shown in Fig. 1, indicate a close match between muscle TE material and beefsteak and water. The $^{238}$Pu transmission data show curvature because the three L-series x rays (13.6, 17.2, and 20.2 keV) have different attentuation coefficients.

## FABRICATION TECHNIQUES

The torso and organ molds are all based on solid plaster casts made from a male cadaver provided by the Anatomy Department at the University of California, San Francisco. The cadaver was 1.77 m tall, weighed 75 kg, and had a chest circumference of 1.01 m. In comparison, a random sample of 500 male LANL and LLNL employees on average were 1.77 m tall, weighed 76 kg, and had a chest circumference of 1 m. The organs and TE replicas are shown in Fig. 2. Organ-replica volumes are presented in Table 1, together with values for Reference Man (ICRP, 1975).

In order to provide the widest range of chest wall thicknesses possible to match a varied worker population, the torso cast of the cadaver had to be modified so that the phantom chest wall overlying the lungs would be as thin as possible while still accomodating the rib cage. This was done by vacuum-forming a plastic sheet on the plaster torso cast to make a thin plastic reproduction of the chest exterior. The sheet was then placed over the cast of the organ cavity and adjusted and mapped to provide minimum chest- and abdominal-wall thickness for the phantom and rib cage. Finally, the torso cast was modified to the desired profile by removing material from the original plaster cast and making a new exterior mold. The final torso model is shown in Fig. 3 together with its mold.

After removal from the cadaver, the rib cage was cleaned to remove soft tissue. A colony of dermestid beetles maintained at the Museum of Vertebrate Zoology, University of California, Berkeley Campus, was used to remove any traces of remaining soft tissue. The beetles were particulary useful for this purpose because they were able to reach small voids in the skeleton (particularly the vertebrae) but did not attack cartilage. Finally, the bones were degreased and filled with Mix-D tissue simulant using a vacuum-filling technique to replace lost marrow in the bone trabeculae. The rib cage assembly was completed by connecting the vertebrae with nylon pins and the ribs with nylon string. Special sections of polyurethane cartilage simulant also connect the ribs to the sternum. The rib cage is shown in place on the organ-cavity mandrel in Fig. 4(a). Figure 4(b) shows the rib cage and the organ-cavity mandrel placed in the torso mold before casting. The mandrel is removed destructively after the torso has cured, and a cut is made for removal of the frontal access plate.

Two additional rib cages were obtained from the Anatomy Department and prepared in a manner similar to the first. These were for the second and third phantoms. All three of the phantoms fabricated at LLNL were intended for use in interlaboratory comparison programs, which required circulation of the phantoms among several laboratories in Europe, Canada, and the United States.

As the intercomparison programs proceeded, it became clear that each of the laboratories involved required the use of the phantoms for longer periods of time than the program schedules allowed. In fact, a number of laboratories expressed interest in having phantoms that could be used as permanent parts of their calibration program. It was therefore decided to fabricate a second set of phantoms on a cost-recovery basis to allow each laboratory individual ownership of its own phantom if desired. As a result, 16 phantoms were made for laboratories in England, Canada, and the United States, and for the International Atomic Energy Agency.

As indicated previously, the new phantoms were nearly identical to the original three, except that a simulated rib cage replaced the real bone used in the original phantoms. This required development of a bone-equivalent material for the ribs and backbone. A "rib bone" composition proposed by Newton and White (1978) was chosen as the reference tissue, and the simulated bones for the new phantoms were made using casts of the real rib cage incorporated into the third of the original phantom set. Casting and assembly of the simulated bone phantom components was done in essentially the same manner as for the original phantoms. Further details concerning the construction and assembly of these phantoms can be found elsewhere (Griffith et al., 1984).

The final major task in phantom construction was the fabrication of TE chest plates to allow simulation of chest-wall attenuation for a wide variety of male statures. The overlays were made to simulate one of three different chest-wall compositions--100% muscle, 50% adipose tissue and 50% muscle, or 87% adipose tissue and 13% muscle--in four thicknesses, thus allowing measurement of chest-wall thickness and composition in the range from 15 to 19 mm without plates to 43 mm with the thickest plates. This range includes more than 95% of the male radiation workers monitored in the United States. Figure 5(a) shows the phantom assembled with an 11-mm-thick chest plate in place. Figure 5(b) shows the phantom and chest plate apart, and Fig. 5(c) shows the phantom with both the chest plate and the frontal access plate removed. Figure 6 shows the phantom in use with paired phoswich detectors as a calibration tool.

## PHANTOM EVALUATIONS

The success of the phantom in an intercalibration program depends on how faithfully it simulates human morphology and radiation transmission through human tissue. A computerized axial tomographic (CAT) scanner at a local hospital was used to help in partial evaluation of these qualities. The CAT scanner yields excellent morphological data through cross-sectional scans. It also provides data on the density of tissue in each section. Figure 7 shows a typical scan of the phantom through the lung region. Comparative tissue densities measured with the CAT scanner for typical human and phantom tissues are shown in Table 2. The CAT scanner data depend on radiation transmission through the tissue; therefore, the agreement in Table 2 indicates that the phantom should provide an accurate measurement of internal attenuation.

Attenuation measurements have been made with the phantom using two 127-mm-diameter phoswich scintillation detectors placed over the lungs. Data for attenuation of L x-rays from $^{238}Pu$ are presented in Figure 8. For comparison, data are shown from both the original phantom set with muscle overlays and the new 16-phantom set without the overlays. Although the new phantoms have chest walls that are thinner than the originals by about 4 mm, performance of the new phantoms matches the originals closely.

As a further test of phantom validity, five laboratories in the United Kingdom and the United States collaborated in an assessment (Newton et al, 1985), designed primarily to check the accuracy of the new phantoms that were produced by Humanoid Systems, Inc. The response from low-energy x rays of the phantom owned by each laboratory was compared to the response from eight men of varied body stature, whose lungs contained $^{92m}Nb$ (a simulant for $^{239}Pu$, emitting 15.8 to 17.7 keV x-rays) in quantities that were known independently of x-ray counting. For paired 127-mm phoswich detectors, the resulting phantom calibration factors compared generally to within ±20% of the average obtained from the human subjects, although individual errors occasionally approached a factor of two. These errors were thought due to detector position and intersubject differences, including distributional effects within the human subjects, in contrast to the phantom lungs, which were uniformly loaded with the calibration radionuclide.

## SUMMARY

Several tissue-equivalent torso phantoms have been fabricated for use by laboratories involved with counting transuranic nuclides in the lung. These phantoms provide the user laboratories with a highly realistic calibration tool that accurately simulates the photon-attenuation properties of human tissue at energies below 20 keV and reasonably reproduces the counting geometry of internally deposited radionuclides, at least where the radionuclide can be assumed to be deposited uniformly in the organ of interest. Use of these phantoms will allow

participating laboratories to intercompare calibration information, both on formal and informal bases.

## ACKNOWLEDGMENTS

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Table 1. Comparative organ volumes.

| Organ | Volume ($cm^3$) Reference Man[a] | Phantom |
|---|---|---|
| Lungs | | |
| Left | 1762 | 1689 |
| Right | 2153 | 2180 |
| Total | 3915 | 3869 |
| Heart | 742 | 748 |
| Liver | 1700 | 2050 |
| Kidney | | |
| Left | 149[b] | 170 |
| Right | | 150 |
| Spleen | 171 | 155 |

[a]Based on Data from ICRP-23.
[b]Distinction between left and right kidneys not made.

Table 2. Densities of tissue and tissue-equivalent plastic as measured by a CAT scanner.

| Tissue | Density ($g/cm^3$) Tissue | TE polyurethane |
|---|---|---|
| Muscle | 1.06 | 1.09 |
| 87% adipose, 13% muscle | - | 1.01 |
| Adipose | 0.92 | - |
| Lung | 0.31 | 0.28 |

## FIGURE CAPTIONS

FIGURE 1. Relative x-ray transmission through tissue-equivalent materials: (a) 16.6-keV x rays from $^{93m}$Nb and (b) 17-keV x rays from $^{238}$Pu.

FIGURE 2. Comparison of real and tissue-equivalent organs: (a) liver, (b) heart, (c) kidneys, and (d) lung, shown with casting mold.

FIGURE 3. Final torso form, shown with silicon casting mold.

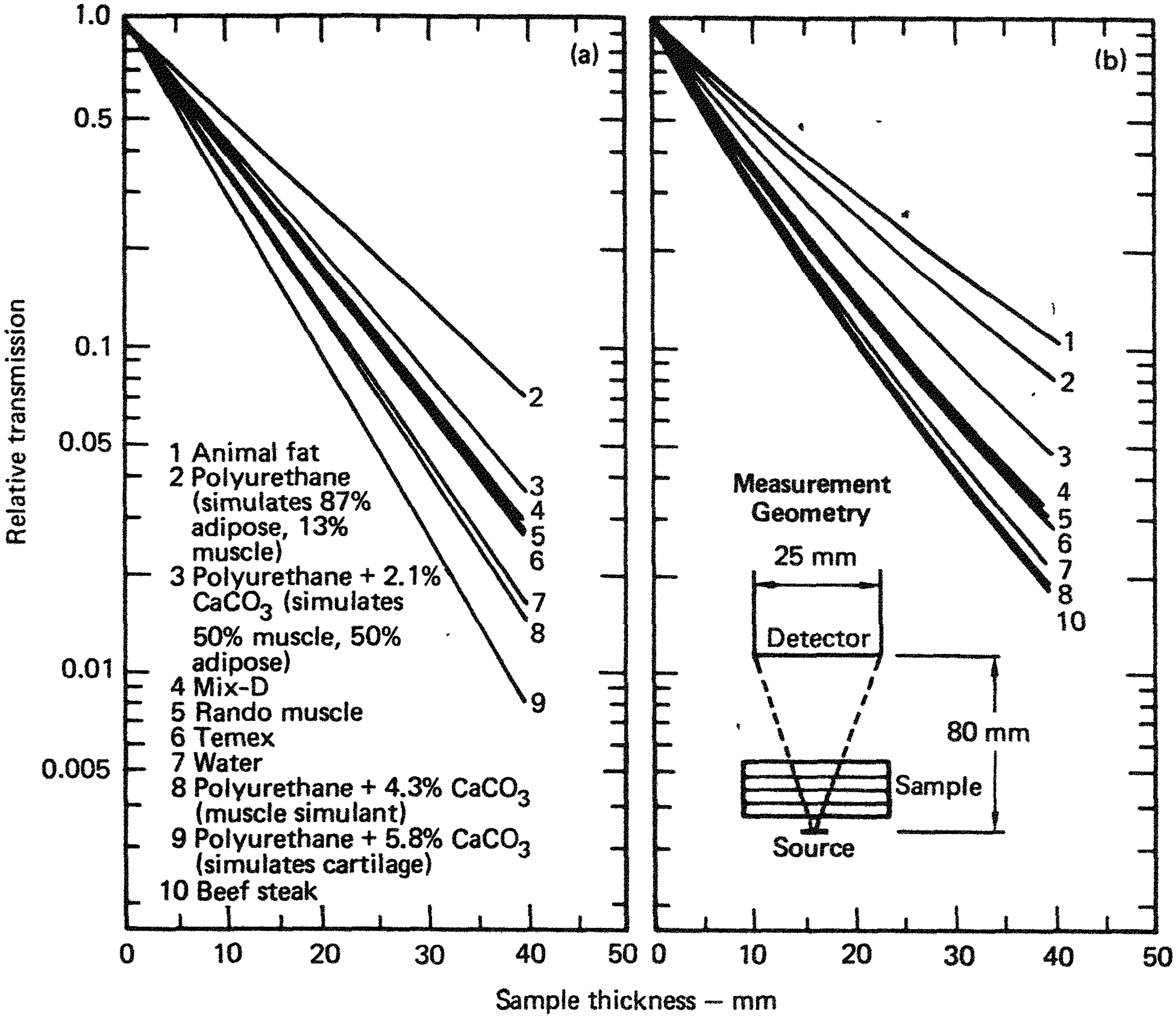
FIGURE 4. Phantom organ-cavity cast with rib cage in place: (a) front view and (b) rear view, showing placement in the torso mold.

FIGURE 5. Completed phantom: (a) with 11-mm-thick chest plate in place, (b) with chest plate removed, and (c) with torso cover removed and model organs exposed.

FIGURE 6. Calibration phantom in use with phoswich detectors.

FIGURE 7. CAT scan shows phantom contour through a section of the chest.

FIGURE 8. $^{238}$Pu calibration factors for phantoms using dual 127-mm-diameter phoswich lung counters.

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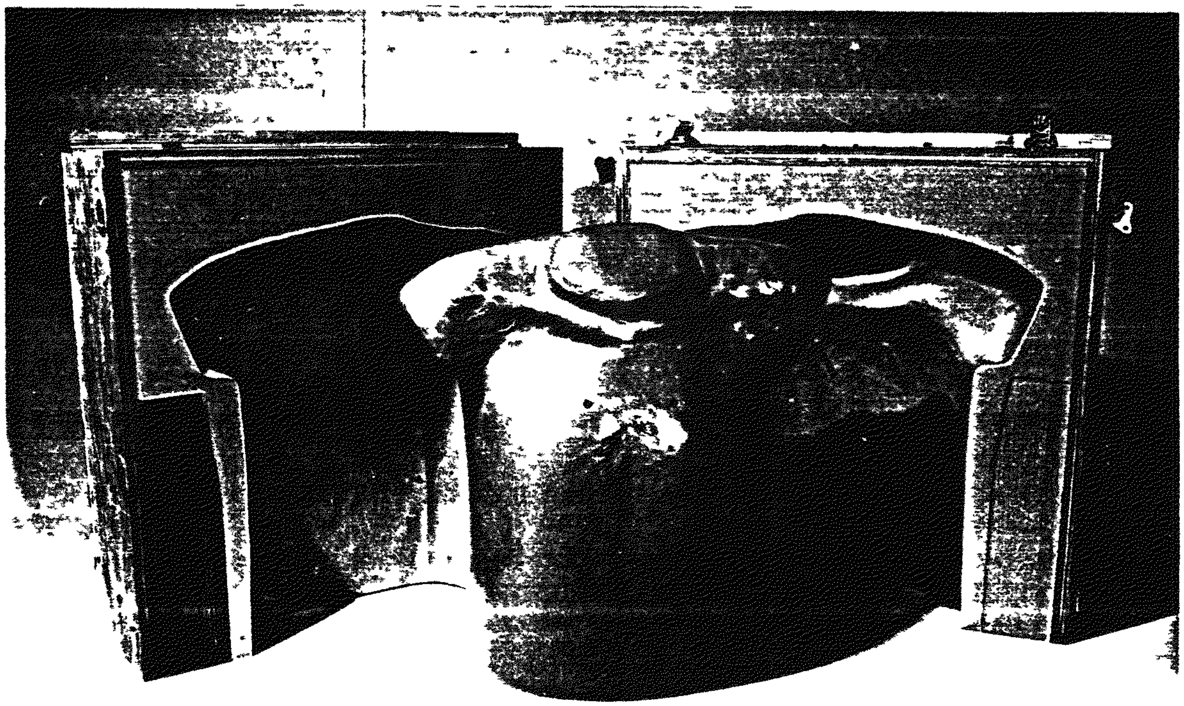

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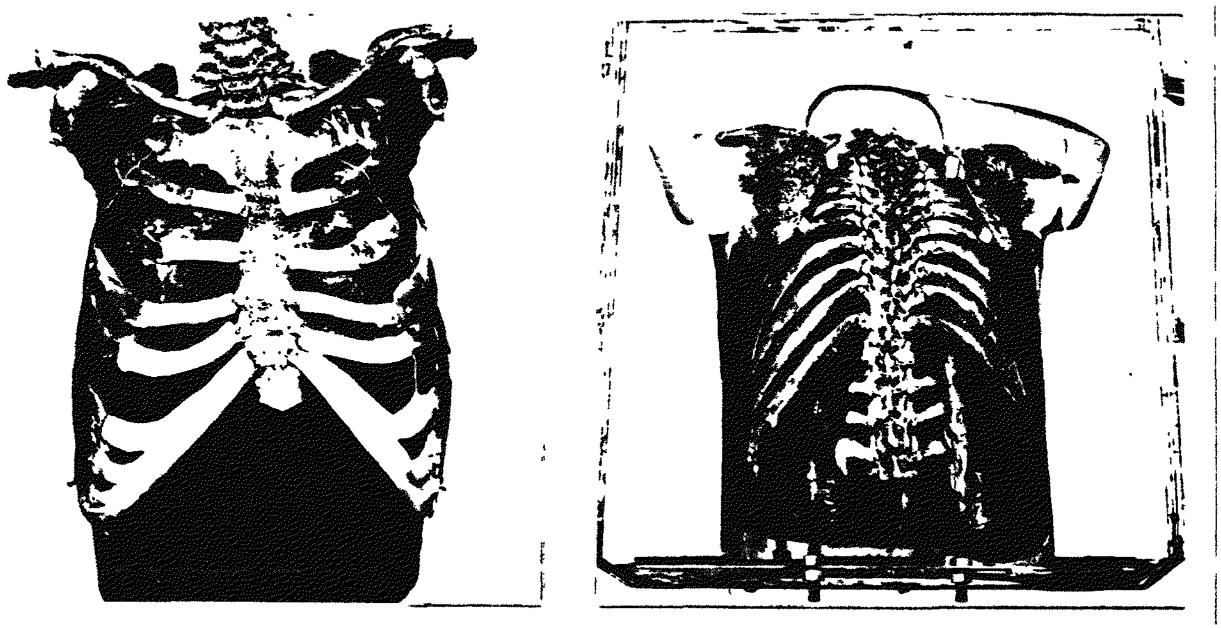

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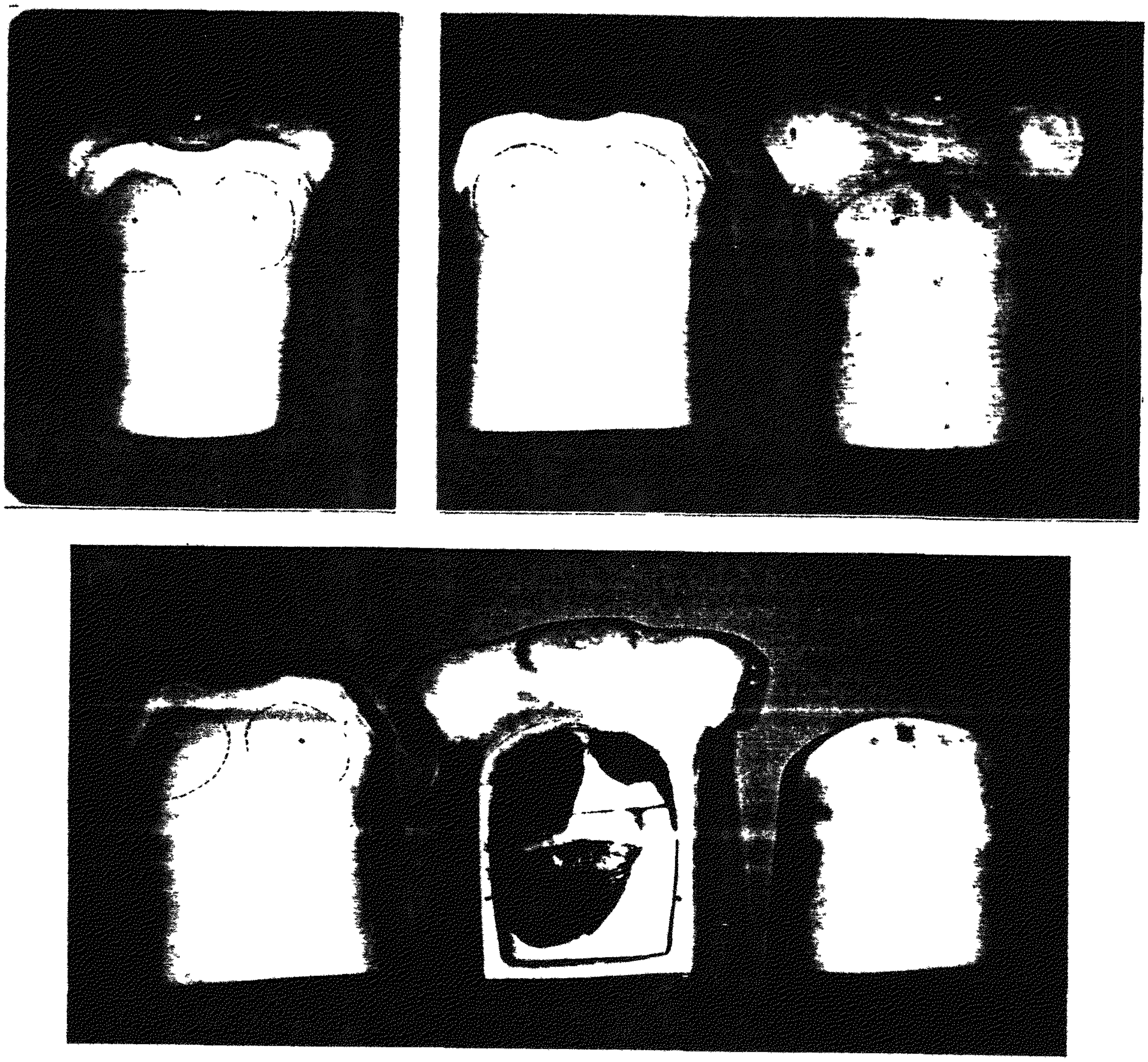

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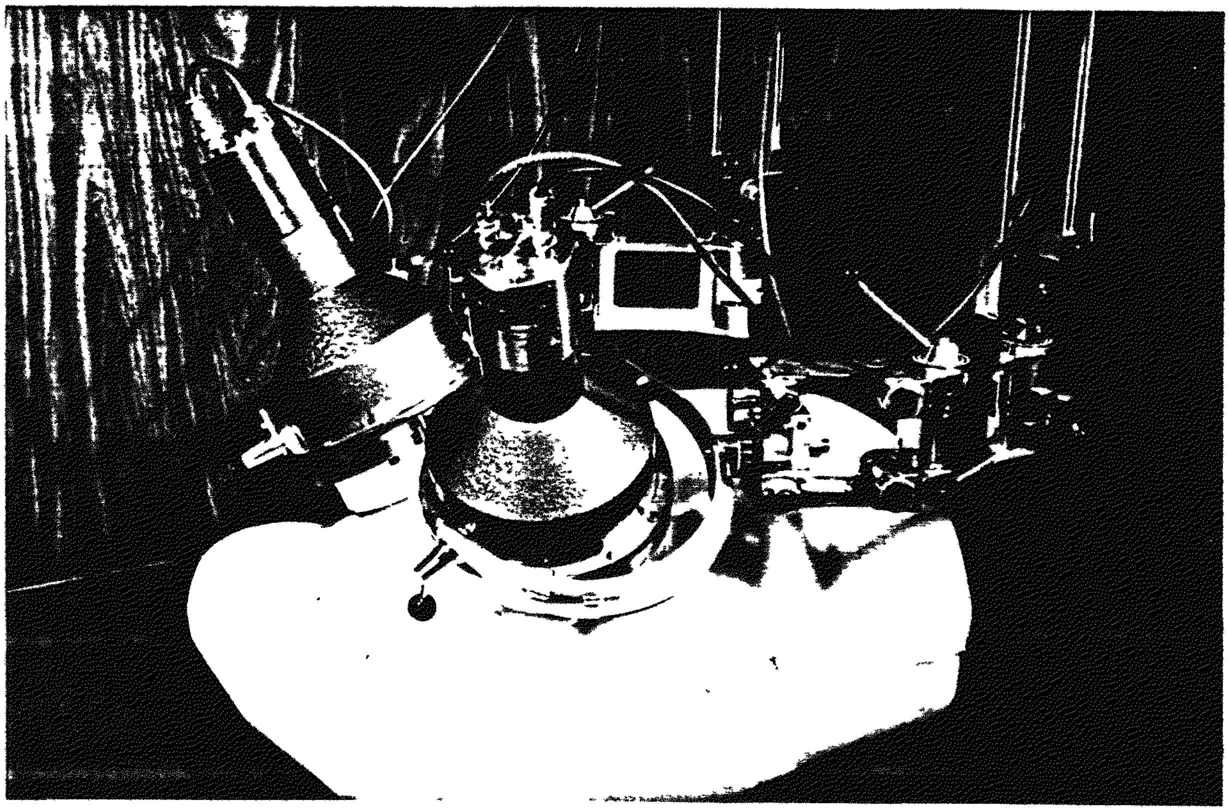

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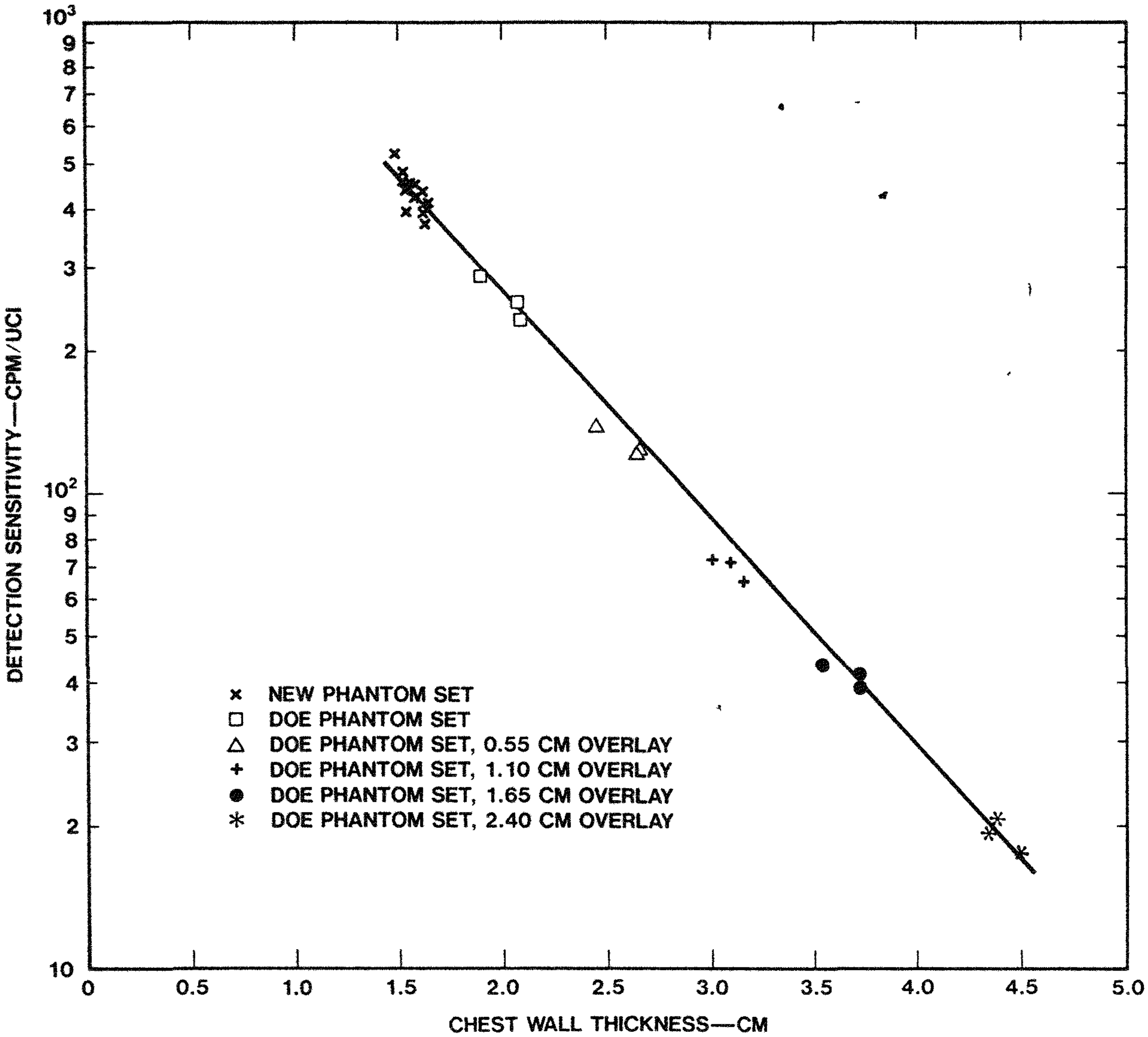


FIGURE 8. $^{238}Pu$ calibration factors for phantoms using dual 127-mm-diameter phoswich lung counters.