1997

History of the Lawrence Livermore National Laboratory Torso Phantom

Frieda Y. Taylor
San Jose State University

Follow this and additional works at: https://scholarworks.sjsu.edu/etd_theses

Recommended Citation

Taylor, Frieda Y., "History of the Lawrence Livermore National Laboratory Torso Phantom" (1997). *Master's Theses*. 1476.

DOI: <https://doi.org/10.31979/etd.k8j3-uvcf>

https://scholarworks.sjsu.edu/etd_theses/1476

This Thesis is brought to you for free and open access by the Master's Theses and Graduate Research at SJSU ScholarWorks. It has been accepted for inclusion in Master's Theses by an authorized administrator of SJSU ScholarWorks. For more information, please contact scholarworks@sjsu.edu.

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

HISTORY OF THE
LAWRENCE LIVERMORE NATIONAL LABORATORY
TORSO PHANTOM

A Thesis
Presented to
The Faculty of the Radiological Health Physics Program
San Jose State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Frieda Y. Taylor

May 1997

UMI Number: 1384725

**Copyright 1997 by
Taylor, Frieda Yvonne**

All rights reserved.

**UMI Microform 1384725
Copyright 1997, by UMI Company. All rights reserved.**

**This microform edition is protected against unauthorized
copying under Title 17, United States Code.**

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

© 1997

Frieda Y. Taylor

ALL RIGHTS RESERVED

APPROVED FOR THE RADIOLOGICAL HEALTH
PHYSICS PROGRAM

Dr. Herbert Silber

Dr. David Hickman, Lawrence Livermore National
Laboratory

Dr. Craig Stone

Dr. Allen Tucker

APPROVED FOR THE UNIVERSITY

ABSTRACT

HISTORY OF THE
LAWRENCE LIVERMORE NATIONAL LABORATORY
TORSO PHANTOM

by Frieda Y. Taylor

This paper summarizes the development and use of the Lawrence Livermore National Laboratory (LLNL) Realistic Torso Phantom. The LLNL Realistic Torso Phantom is used to calibrate detectors for the measurement of photon-emitting radionuclides that are internally deposited in organs in the human torso. In 1974, the design criteria for the realistic phantom were established by the Intercalibration Committee for Low-Energy Photon Measurements. The Committee's objectives were to develop methods to improve the sensitivity and precision of detector systems used to assay transuranic elements in the human lung, to identify and resolve weaknesses that existed in calibration techniques, and to execute a program to intercalibrate detector systems in use at the Department of Energy (formerly ERDA) laboratories. The developmental approach taken by the committee was to model the phantom using a human cadaver. Varied studies were subsequently performed that validated the LLNL realistic phantom as a calibration tool.

ACKNOWLEDGMENTS

This work is dedicated with all my love to my husband, Alfred, my son, Alfred, my daughter, Nia, and my parents. Also, a special thanks to my friend and academic advisor, David P. Hickman, Ph.D.

There are others whom I have not mentioned individually. To those, I extend my gratitude and thanks. Finally, it would be remiss of me not to acknowledge that, "I can do all things through Christ who strengthens me."

TABLE OF CONTENTS

I. INTRODUCTION	1
II. EARLY HISTORY	1
III. FABRICATION.....	9
IV. SECOND-GENERATION OF PHANTOMS.....	19
V. ADDITION OF RADIONUCLIDES TO THE ORGANS.....	22
VI. TESTING AND VERIFICATION OF THE PHANTOM.....	23
VII. SUMMARY	31
VIII. REFERENCES	32
IX. APPENDIX A: TABLES FOR THE DESIGN CRITERIA FOR THE LLNL PHANTOM AND PARTICIPATING LABORATORIES	35
X. APPENDIX B: FIGURES.....	42
XI. APPENDIX C: MEASUREMENT DATA FOR THE SECOND- GENERATION OF PHANTOMS.....	48
XII. APPENDIX D: PRELIMINARY CHECKS FOR THE SECOND- GENERATION OF PHANTOMS.....	63
XIII. APPENDIX E: COMPARATIVE ORGAN CALIBRATION DATA FOR THE SECOND-GENERATION OF PHANTOMS.....	65

APPENDIX A: LIST OF TABLES FOR THE DESIGN CRITERIA FOR THE LLNL PHANTOM AND PARTICIPATING LABORATORIES

- Table A.1. Dimensional data on "standard man" laboratory personnel, and the cadaver.
- Table A.2. Comparative organ volumes (cm³).
- Table A.3. Photon emission data from three transuranic isotopes used in the design of the LLNL phantom.
- Table A.4. Polyurethane formulations for tissue substitutes.
- Table A.5.a. Elemental compositions and densities for reference tissues.
- Table A.5.b. Elemental compositions and assumed densities for tissue substitutes.
- Table A.6. Calculated photoelectric attenuation coefficients for reference tissues and tissue substitutes as a function of photon energy.
- Table A.7. Second-generation of phantoms, sixteen participating laboratories.
- Table A.8. Abbreviations for laboratories.

APPENDIX B: LIST OF FIGURES

- Fig.1. Calculated photoelectric attenuation coefficients for muscle vs. water vs. LLLM1 and LLLM2 (tissue substitutes) as a function of photon energy.
- Fig.2. Calculated photoelectric attenuation coefficients for lung (tissue) vs. LLLL1 (tissue substitute) as a function of photon energy.
- Fig.3. Calculated photoelectric attenuation coefficients for adipose (tissue) vs. LLLA1 (tissue substitute) as a function of photon energy.
- Fig.4. Calculated photoelectric attenuation coefficients for cortical bone - rib vs. LLLR1 (tissue substitute) as a function of photon energy.
- Fig.5. Calculated photoelectric attenuation coefficients for reference tissues as a function of photon energy.

APPENDIX C: LISTS OF TABLES OF MEASUREMENT DATA FOR THE SECOND-GENERATION OF PHANTOMS

- Table C.1. Thickness measurements for the torso core.
- Table C.2. Liver circle placement for the torso core.
- Table C.3. Lung detector circle distance, 87% fat chest overlays.
- Table C.4. Lung detector circle distance, 50% fat chest overlays.
- Table C.5. Lung detector circle distance, 100% muscle chest overlays.
- Table C.6. Liver circle placement (vertical distance), 87% fat chest overlays.
- Table C.7. Liver circle placement (vertical distance), 50% fat chest overlays.
- Table C.8. Liver circle placement (vertical distance), 100% muscle chest overlays.
- Table C.9. Thickness measurements: 87% fat chest overlays, 1st and 2nd overlays.
- Table C.10. Thickness measurements: 50% fat chest overlays, 1st and 2nd overlays.
- Table C.11. Thickness measurements: 100% muscle chest overlays, 1st and 2nd overlays.
- Table C.12. Thickness measurements: 87% fat chest overlays, 3rd and 4th overlays.
- Table C.13. Thickness measurements: 50% fat chest overlays, 3rd and 4th overlays.
- Table C.14. Thickness measurements: 100% muscle chest overlays, 3rd and 4th overlays.

APPENDIX D: LIST OF PRELIMINARY CHECKS FOR THE SECOND- GENERATION OF PHANTOMS

- Table D.1. Preliminary checks for the torso cores for the second-generation of phantoms.
- Table D.2. Preliminary checks for the chest overlays for the second-generation of phantoms.

APPENDIX E: LIST OF TABLES OF THE COMPARATIVE ORGAN
CALIBRATION DATA FOR THE SECOND-GENERATION OF PHANTOMS

Table E.1. Comparative organ calibration data for the ^{238}Pu lung sets.

Table E.2. Comparative organ calibration data for the ^{239}Pu lung sets.

Table E.3. Comparative organ calibration data for the ^{241}Am lung sets.

I. INTRODUCTION

Prior to the development of the LLNL torso phantom, there were discrepancies in the various calibration methods used to assess plutonium in organs. These discrepancies were attributed, in part, to the common use of materials whose x ray attenuation properties were quite different from the tissues they were intended to represent. Today, significant improvements have been made in the calibration of x ray counters for the assessment of plutonium in organs using realistic phantoms containing anthropomorphic organ sets with known quantities of radionuclides. Another, but less commonly used method of calibration (*in vivo*) is obtained by depositing independently known quantities of some short-lived, low-energy x ray emitters in the lungs of volunteers (Newton et al. 1981).

II. EARLY HISTORY

In 1970, the Intercalibration Committee for Low-Energy Photon Measurements established a forum to discuss and compare plutonium whole-body counting data and techniques. At its meeting (during the 1970 Health Physics Society meeting), the committee identified several problems associated with the calibration of *in vivo* measurement systems for the assessment of actinides (Anderson et al. 1979):

- Isotopically pure ^{239}Pu is known to be the most difficult actinide to detect and measure in the human lung.
- The allowable occupational intake is small.
- None of the high-energy gamma lines associated with the decay of plutonium occur with enough intensity to make it practical to count them, and there are essentially no K x rays.
- The L x rays accompanying the alpha-decay process are the most abundant photons available for measurement, and they are not very intense.
- The low-energy 17-keV L x rays are heavily attenuated in bone and tissue so that very few x rays emerge from the body. Each 1-mm error in thickness has been known to produce an error in the calibration factor of approximately 12%.
- There are uncertainties in the composition and thickness of overlying tissue.

Further, several considerations influence the emerging radiation fluxes from the anterior surfaces of the thorax (Newton and White 1978):

- The nature and thickness of the chest wall soft tissues.
- The extent to which the rib cage and the sternum screen the lungs from the detector.
- The loss of photons by attenuation within the lungs.

- The scattering and screening effects of other thoracic organs (e.g., the heart and liver).

The primary problem associated with lung counting is the variability or uncertainty in the fat content of the chest wall. One transmission measurement study showed the fat content in the human chest wall varies from 10% to 34%, with the mean value being approximately 22% (Anderson et al. 1979).

Various types of detection systems were commonly used to measure actinides in the human lung. Two of the most commonly used systems are phoswich or germanium detectors. The phoswich detectors are used to measure low-energy photons, and are typically placed high on the chest and tangent to the sternum with one detector over the right lung and the other over the left lung. Intrinsic germanium planar arrays are systems that have multiple detectors over each lung and have good energy resolution (Anderson et al. 1979). For more information regarding phoswich detectors, germanium detectors, and planar germanium arrays used for *in vivo* measurements, see Laurer 1968 and Falk et al. 1978.

At the Health Physics 1970 meeting, the Intercalibration Committee decided to undertake an intercalibration program that comprised three phases. Phase 1 involved the accumulation and tabulation of basic data on photon intensities from the isotopes of interest, and was completed in 1971. Phase 2 involved the performance of an intercomparison of counting systems

using a standardized source. And phase 3 involved measuring volunteers who intentionally inhaled a mock plutonium (Swinth 1973).

The purpose of phase 2, the source intercalibration portion of the program, was to show how the individual laboratory was performing relative to other laboratories. But the committee determined that routing of a phantom would be too cumbersome. Therefore, phase 2 was accomplished using isotopically pure point sources (^{238}Pu and ^{241}Am) counted in a standard geometry. A simple calibration stand was used to control the geometry during the measurement. The results of phase 2 showed that there was instrumental control between the laboratories; calibration differences were due to differences in calibration standards; and the final comparison depended on intercalibration with human volunteers exposed to a mock plutonium (to be accomplished in phase 3) (Swinth 1973).

Initiated in 1972, phase 3 comprised an interlaboratory exercise conducted to assess techniques of detection and calibration in the direct measurement of lung contamination. A mock plutonium emitting only low-energy x rays was used. Three volunteers of small, intermediate, and large physiques inhaled an insoluble aerosol incorporating ^{103}Pd , a 20-keV x ray emitter. They visited 14 laboratories in the United Kingdom (U.K.), Europe, and North America. Participants in the exercise were asked to estimate each subject's lung content using their respective procedures for assessing the plutonium lung burden. Their estimates were compared with values derived

independently from gamma-ray measurements of ^{51}Cr , which had also been incorporated in the inhaled particles. The 325-keV gamma photon emitted from ^{51}Cr enabled the laboratories to measure the retention of the aerosol particles and hence standardize the ^{103}Pd content of the subjects' lungs at a given stage (Newton et al. 1978).

In most cases, calibration procedures at the laboratories were based on different styles of thorax phantoms. Most of the laboratories underestimated the amount of activity in the subjects in some instances by as much as a factor of 3 or more (Newton et al. 1978). Therefore, estimates of pulmonary contamination, which were derived by external counting of low-energy x rays, were grossly unreliable. The use of the commercially developed lung substitutes is believed to have contributed substantially to the errors observed by several of the participating laboratories.

Further efforts to resolve the differences observed among the laboratories resulted in the formalization of an intercalibration effort within the United States (U.S.) in 1974 through the Intercalibration Committee for Low-Energy Photon Measurements. The committee originally comprised representatives from Argonne National Laboratory, Battelle Pacific Northwest Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Mound Laboratory (Monsanto), and Savannah River Ecology Laboratory. The committee was sponsored by the Energy Research

and Development Administration (ERDA). The committee's objectives were to (Dean et al. 1975):

- Develop methods for improving the sensitivity of detector systems for assaying transuranic elements in the human lung.
- Identify and resolve the weaknesses that existed in calibration techniques at that time.
- Execute a program to intercalibrate the detector systems in use at ERDA supported laboratories.

On the basis of the early intercalibration efforts, the committee concluded that the phantoms in use at that time were mostly inadequate and therefore were not designed to detect x ray emitters in the human lung (Dean et al. 1975). Consequently, the need for a realistic calibration phantom was warranted. The committee concluded that a realistic phantom needed to (Griffith et al. 1986):

- Reproducibly simulate the counting geometry of internally deposited radionuclides.
- Be made of materials that simulate the photon attenuation properties of human tissue (muscle, bone, adipose, cartilage, liver, and lung) at energies below 20-keV.
- Be rugged enough for use in routine laboratory and interlaboratory calibration programs.

The initial phantom design criteria that the DOE Intercalibration Committee agreed upon were sevenfold (Dean et al. 1975):

1. Reference (standard) man dimensions were to be used where possible. Because there was such a large difference between the data for standard man and the average worker, the committee decided to use the average dimensions for employees routinely measured for plutonium, augmented with standard man data where necessary.
2. Only the upper trunk (neck to waist) was to be represented.
3. The organs to be included were the heart, liver, lungs, kidneys, spleen, lymph nodes, and trachea.
4. The organs had to be easily removed.
5. A human skeleton (caucasian) with a unit density (i.e., 1.0 g/cm^3) marrow cavity, was to be used.
6. The use of tissue substitutes was required throughout the process. The lung density was specified at 0.25 g/cm^3 .
7. The average chest wall thickness and chest profile were to be changeable.

The developmental approach selected by the committee was to model the phantom from a human cadaver selected to closely match the height, weight, and chest circumference of the average plutonium process worker. Final dimensional data used in the design of the realistic phantom as well as data for the cadaver and standard man (Dean et al. 1975) are provided in Table

A.1. Table A.2. contains organ volumes and the values for “reference man” and the phantom (Griffith et al. 1986).

The first-generation of phantoms comprised three realistic phantoms that were fabricated at LLNL using the design criteria specified by the Intercalibration Committee. These phantoms were circulated among several laboratories in Europe, Canada, and the United States. Each of the first-generation of phantoms simulated a human male torso, without a head or arms, and terminated just above the pelvis, and was designed to be measured on the ventral portions. The dimensions of the phantoms (height, weight, and chest circumference) were based on the anatomical average of 500 typical radiation workers from Los Alamos National Laboratory and Lawrence Livermore National Laboratory (see Table A.1.). Each phantom comprised tissue substitutes with the following features (Griffith et al. 1986):

- A polyurethane torso shell with an imbedded human male rib cage.
- Removable lungs, heart, liver, lymph nodes, and additional material simulating intestines and body fluids that filled the phantom cavity.
- Chest plates that overlaid the phantom simulating the geometry and chest-wall attenuation of a range of statures seen in male radiation workers.
- Three sets of chest plates simulating tissue attenuation provided by increasing thicknesses of lean muscle or a combination of adipose and muscle (50% of each by weight, or 87% adipose and 13% muscle).

Initially, kidneys made of a tissue substitute were prepared for use with the phantom, but were not used in the final commercial versions of the phantom (Griffith et al. 1986). Due to the translocation of plutonium to the lymph nodes, a hollow trachea and the three major lymph node regions were also included, thus enabling the phantom to be used to calibrate intraesophageal probes that were used to detect plutonium in the lymph nodes (Dean et al. 1975). Additionally, a 1-cm diameter channel that permitted calibration with esophageal detectors was included behind the tracheobronchial plane of the phantom (Griffith et al. 1986).

III. FABRICATION

Several preliminary steps were taken to assure the proper fabrication of the realistic phantom (Griffith et al. 1975):

- Acquisition of a human rib cage and major organs from a male cadaver of the same specified stature.
- Molding of the torso and interior void of the cadaver with organs removed.
- Preliminary selection of tissue substitutes.

Using the dimensional criteria previously described, a human cadaver was selected from the Anatomy Department at the University of California, San Francisco (Griffith et al. 1986). Solid plaster casts were made of the torso and

organs of the cadaver. From the plaster casts, torso and organ molds were constructed.

Preliminary selection of tissue substitutes necessitated the establishment of a baseline definition. Therefore, a tissue substitute (tissue equivalent material) was defined as a material that has the same linear transmission properties as the human tissue being simulated for photons with energies as low as 13-keV. Other considerations paramount in the selection of a tissue substitute were

- The tissue being simulated, its density, effective atomic number (Z), electron density (Griffith et al. January 1976), attenuation properties, and variability of composition for density simulations (Griffith et al. 1986).
- The elemental compositions of the tissue substitute to ensure conformity between the reference tissue and the tissue substitute (Newton and White 1978).
- The type of radiation being used and the interaction parameter(s) in question (Griffith et al. January 1976).
- The ability of the tissue substitute to be formed into irregular shapes.
- The durability of the tissue substitute (minimizing deformation over many years) (Griffith et al. 1986).

- The relative contributions from scattered photons due to adjacent organs (Newton and White 1978).

Through the evaluation of various tissue substitutes, it was acknowledged that, although it was not necessary to match each of the attenuation properties to achieve functional simulation (Griffith et al. January 1976), the photoelectric attenuation coefficients had to be matched when selecting tissue substitutes that were valid for 13-keV to 20-keV photons. Coherent scattering was assumed not to result in any net loss in the response of large-area detectors and therefore was not taken into account. Finding substitutes that satisfied the flexible requirements for Compton scattering was not difficult, because Compton scattering is a relatively unimportant process of attenuation at or below 20-keV. Compton scattering attenuation coefficients are much less dependent on atomic number (Z) than are the photoelectric attenuation coefficients, and show correspondingly less variation among soft tissues and a wide range of low Z materials (Newton and White 1978). Table A.3. lists the photon emissions of the three most important transuranic isotopes[§] considered in the construction of the phantom (Griffith et al. January 1976).

The reference simulated included bone, muscle, bone marrow, adipose, cartilage, and lung material. A human rib cage provided the necessary bone

[§]The phantom was designed to the photon emissions in Table A.3. These photon emissions do not represent current values for the isotopes.

structure, but the other tissues were simulated with plastic materials. A muscle substitute that made up the greatest portion of the phantom mass was used for add-on layers of chest tissue over the lungs and for the major organs, except for the lungs. An adipose substitute was also developed for add-on layers. Cartilage, which has a density approximately 10% greater than muscle, was only used to connect the ribs to the sternum (Griffith et al. January 1976).

A number of formulations have been published as tissue substitutes. Epoxy-based formulations provided an accurate basis for tissue substitutes for a wide variety of human tissues. But there were challenges with handling the epoxy-based formulations because they were too rigid (Griffith 1980). Consequently, polyurethane^{ss} was selected for use as the base material for tissue substitutes due to its flexibility, durability, and low Z composition (Griffith et al. January 1976). Water was chosen as the transmission standard (reference for simulation) for lean tissue (muscle) because of similar transmission properties and the availability as a reproducible absorber (Griffith et al. January 1976). In selecting a proper filler, it was best to select materials with atomic numbers lower than 20. If high Z fillers (such as KCl) had been used, it would have been more difficult to match the attenuation coefficients of tissues over the range of energies from 10-keV to 100-keV.

^{ss} The density range for polyurethane is 1.03 to 1.08 g/cm³.

In contrast, if very low Z materials had been used, the quantities required to achieve the proper attenuation may have exceeded the capacity of the polyurethane. Calcium carbonate (a filler) was considered and later used to adjust the density (Griffith et al. 1975). Table A.4. provides the original polyurethane formulations (tissue substitutes) for muscle, adipose, bone, and lung. Table A.5.a. lists the elemental compositions and densities for reference tissues. Table A.5.b. lists the elemental compositions and estimated densities for tissue substitutes.

Table A.6. shows the validity of the tissue substitutes used for the LLNL torso phantom. The table also shows a comparison of the photoelectric attenuation coefficients for the reference tissues with the tissue substitutes at 13 selected energies, up to 100-keV. These photoelectric attenuation coefficients were calculated using the computer program XCOM (Berger and Hubbell 1987) and the elemental composition data from Tables A.5.a. and A.5.b. Figures 1 through 4 demonstrate that the tissue substitutes selected for fabricating the phantom successfully simulated the transmission properties of the human torso. Figure 5 shows that the photoelectric coefficients for the reference tissues, the deflated lung, and the muscle tissues are essentially equal.

After selecting the tissue substitutes, the construction of the first-generation of phantoms commenced. Concerns regarding the use of “standard man” organs were addressed during a tour of the dissection

laboratory at the Anatomy Department at the University of California, San Francisco. Observations were made regarding the large variability in organ shapes and sizes. Because of the noted variability, there were also concerns regarding organs fitting together properly in the torso (organ cavity) mold (Griffith et al. 1975).

The original cast of the torso was made by filling the cadaver void with expanding silicon foam. Because there was some shrinkage in the original foam cast, it was necessary to modify the plaster cast until the rib cage fit properly (Griffith et al. 1975). A major concern was minimization of voids in the torso after casting. To verify this, x rays were taken of the torso mold at energies from 75-kV to 300-kV. There were no significant voids greater than 3 mm. Additionally, because the chest plate was thin enough to be translucent, an optical radiograph was also taken using an incandescent back light. Likewise, no significant voids were observed with the optical radiograph (Griffith et al. 1977).

After removal from the cadaver, the rib cage was cleaned to remove the soft tissue including the bone marrow. A colony of Dermestid beetles^{§§§} was used to remove any traces of remaining soft tissue. Use of the beetles was advantageous because of their ability to reach small voids in the skeleton (particularly the vertebrae) without attacking the cartilage. After the bones

^{§§§}The colony of Dermestid beetles was maintained at the Museum of Vertebrate Zoology at the University of California, Berkeley.

were cleaned and degreased (using ammonia and a vapor solvent) (Griffith et al. 1978), the bone marrow was replaced by filling the bones with Mix-D[‡] a bone marrow substitute (Griffith et al. 1986). This process required the bone to be suspended over a pot of molten Mix-D in a vacuum chamber. The bone was then lowered into the fluid Mix-D and the chamber was brought to atmospheric pressure, forcing the tissue substitute into the trabeculae of the bone. The mixture was subsequently cooled. The bone was removed from the chamber (prior to the solidification of the Mix-D), then excess Mix-D was removed from the bone (Griffith et al. 1975). Traces of the Mix-D remaining were removed from most of the rib surface by micro-blasting with CaCO₃ to improve the bond of the polyurethane after phantom assembly (Griffith et al. January 1976). Neutron radiography was used to verify that addition of the Mix-D to the bone marrow cavities had been achieved.^{‡‡} To assure proper evacuation and penetration of the Mix-D, the entire process took approximately one day (Griffith et al. 1975).

The rib cage was reassembled using nylon pins to fasten vertebrae and nylon lines to hold the ribs at the proper spacing. Cartilage segments that

[‡]The elemental composition of Mix-D (ICRU 1989) is H-13.4, C-77.8, O-3.5, Mg-3.9, Ti-1.4. The density is .990 g/cm³.

^{‡‡}Unpublished document from LLNL's whole-body counter files. Letter dated April 12, 1996, from Richard V. Griffith, Special Projects Division, Hazards Control Department, to Wade J. Richards.

were made of a tissue substitute connected the ribs to the sternum. The assembled rib cage was then placed on the torso mold (Griffith et al. 1977).

Two additional rib cages were obtained and used for the second and third phantoms of the first generation. Although there were some differences, the new rib cages appeared to fit well on the existing organ cavity mold. The second rib cage represented an example of human anatomical variability. There was a bifurcation of the cartilage that connected the third rib on the left side to the sternum. As a result, the rib itself was unusually wide at the point of cartilage attachment. This is not uncommon, and usually occurs during embryonic development. To maintain the uniformity of the three phantoms, the third rib (of the second rib cage) was trimmed prior to construction and replaced with plastic cartilage (Griffith et al. July 1976).

There were challenges that had to be resolved prior to casting the organs. After removal from the cadaver, the lungs began to deflate. Casting could not be accomplished without serious distortion. Therefore, a simple specimen preparation technique was used to make the lungs rigid for casting. The lungs were inflated and dried by passing a tube into the trachea, which was still attached to the lungs. Compressed air was then allowed to flow through the lungs for approximately two weeks. It should be noted that the glycerin in the embalming fluid left most of the lungs somewhat spongy, but rigid enough for casting. The heart, liver, spleen, and kidneys were also left

sufficiently rigid as a result of the embalming technique. The individual organs were cast as follows (Griffith et al. 1975):

- The organs were suspended into a box on the points of hypodermic needles, which were inserted through the sides of the box.
- The box was filled with polyurethane.
- After the polyurethane solidified, the newly formed molds were removed.
- The model organs were made of non-shrinking plaster using the newly formed molds.

Comparisons of the final organ volumes with respect to the International Commission on Radiation Units and Measurements (ICRU) values are provided in Table A.2.

Chest plate overlays composed of a tissue substitute were developed as a set of four overlays that covered the torso to a line below the parting line in the torso.^{††} These plates were fabricated for placement over the phantom torso 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: (1) 100% muscle, (2) 50% adipose tissue and 50% muscle,

^{††}Unpublished document from LLNL's whole-body counter files. Draft letter to each of the 16 participating laboratories requesting a second-generation phantom.

and (3) 87% adipose tissue and 13% muscle (^I and Griffith et al. 1986). The overlay thicknesses were constant across the frontal surface of the torso, tapering to the side along a lateral plane 13 cm from the frontal surface of the torso.^{II}

Molds were made for four nominal chest plate overlay thicknesses (6, 11, 16 and 24 mm). Together with the basic torso, this provided five measurements of chest wall thicknesses and compositions. This range represented more than 95% of the male radiation workers monitored in the United States at that time (Griffith et al. 1978). The chest plates were intended to be used only one at a time, not in combination. Although two or more of them could have been used together, they would have distorted the natural geometry thus making reproducibility of phantom measurements uncertain.^{III}

^IThe tissue substitute for adipose which is LLLA1 (refer to Table A.4.) was pure polyurethane. Therefore, that is the actual composition these chest plates simulated. Private communication with Richard V. Griffith, IAEA.

^{II}Unpublished document from LLNL's whole-body counter files. Draft letter to each of the 16 participating laboratories requesting a second-generation phantom.

^{III}Private communication with Dr. David Hickman, Lawrence Livermore National Laboratory.

IV. SECOND-GENERATION OF PHANTOMS

As the intercomparison program proceeded, it became clear that each of the participating laboratories required the use of phantoms for longer periods of time than the program's schedules allowed. Several laboratories expressed an interest in having phantoms that could be used as permanent parts of their calibration programs; hence, the fabrication of a second-generation of 16 phantoms. Each of the 16 phantoms was to be fabricated on a cost recovery basis, thus providing each of the 16 participating laboratories with individual ownership. Table A.7. lists the participating laboratories (Griffith et al. 1986).

The primary goal established for the fabrication of the 16 phantoms was to duplicate the first-generation of phantoms as closely as possible. Because of a lack of standard-sized "true bone," the bone structure used in the first-generation of phantoms had to be replaced with a bone simulant. The use of simulated bone was also driven by the practical problems of obtaining 16 human rib cages and the legal and ethical requirement of burying the human bones after the useful life was over.[#] The second-generation of phantoms were identical to the original three, with the exception that a simulated rib cage replaced the real bone. This required the development of a bone substitute to replace the ribs and the backbone (Griffith et al. 1984). Another subtle difference between the first and second-generation of phantoms was

[#]Private communication with Richard V. Griffith, IAEA.

that the second-generation of phantoms had core chest walls that were thinner by approximately 4 mm (Griffith et al. 1986).

Reproducibility was and continues to be an important aspect in the use of the realistic phantoms. This resulted in the development of a marking system for the frontal surfaces of the phantoms as well as for each overlay. The basis was the critical positioning, centered over each lung and the liver, for the external detector measurements. A pattern of three concentric circles, extending in 1-inch increments to five inches in diameter, was applied to the phantoms and overlay surfaces at these three positions. Refer to Appendix C for data corresponding to the lung and liver circle placements. Additionally, a coordinate system formed by a 1-cm $\times$ 1-cm rectangular grid was projected on the torso or chest plate surfaces. This provided a reference for counting requirements that necessitated special detector positioning. The grid patterns were alphanumerically labeled with letters on one axis and numbers on the other axis thus providing an identifier that could be referenced on any phantom or chest overlay (Griffith et al. 1984).

Although the concern and goal were to make the 16 torsos and other phantom components as geometrically reproducible as possible, there were some variations from component to component. For example, the lateral position of any given reference point was expected to be within ± 2 mm with

respect to the torso bone and cartilage structure for the 16 torsos produced in this work.^{##}

An important factor to consider in using the phantoms was the effective thickness of the material representing the chest wall for both the 16 torsos and the tissue-equivalent chest plates. The thickness was measured at 47 locations evenly distributed over the concentric circles located over the lungs and liver on the torso covers as well as all chest plates. The effective thickness for each pattern area was then determined using an exponential-averaging technique. It was acknowledged that areas on the torso having different thicknesses would not normally have equal contributions to the effective transmission of L x rays from transuranic nuclides. Therefore, an algorithm was developed to calculate the effective thickness under each detector. Based on data from measurements of the transmission of plutonium x rays through beefsteak, the following formula was developed to predict the transmission (I/I_0) from the physical thickness (X) of muscle:^{##}

$$I/I_0 = 1.01045 - 1.28258X + 0.838006X^2 - 0.345726X^3 + 0.937023X^4 - 0.0165166X^5 \\ + 1.81059 \times 10^{-3} X^6 - 1.11400 \times 10^{-4} X^7 + 2.91947 \times 10^{-6} X^8,$$

where X is the thickness of muscle in cm.

The thicknesses of 47 points uniformly distributed over the 5-inch diameter

^{##}Unpublished document from LLNL's whole-body counter files entitled, "Counting Position Markings and Chest Thickness Data."

counting circles were measured. The 47 transmission values were calculated and averaged. The effective transmission was used to back-calculate the effective thickness, X .^{###}

To track the prospective differences in the second-generation of phantoms, checklists, data sheets, and lung density data sheets were used. A checklist was completed for each of the 16 participating laboratories, but was not published. The categories comprising the checklists included preliminary checks (see example in Appendix D), thickness measurements for the core and chest overlays, and concentric circle placements for the lungs and the liver. Appendix C contains a summary of the measurement data corresponding to the second-generation of phantoms.

V. ADDITION OF RADIONUCLIDES TO THE ORGANS

The process of adding a radionuclide to an organ required the isotope to be uniformly distributed throughout the organ. This was initially accomplished by dissolving the radionuclide in nitric acid, together with a small amount of lanthanum nitrate carrier and acetone. The solution was mixed well with the polyurethane before casting, resulting in uniform organ labeling (Griffith et al. July 1976; Griffith 1980).

^{###}Unpublished document from LLNL's whole-body counter files entitled, "Counting Position Markings and Chest Thickness Data."

The most difficult organ to add a radionuclide to, and assure uniform distribution, was the lung. The difficulty was largely due to the acceleration of the foaming process. Use of the acetone was helpful because it facilitated in preventing the inadvertent introduction of water, which caused the acceleration of the foaming process (Griffith et al. July 1976).

To test the loading uniformity, a lung was made and a sole solution of lanthanum carrier (no radioactive material) was added. The lung was then sliced along the plane having the largest cross-sectional area. Using x ray fluorescence, the relative concentration of lanthanum in the lung was plotted. Thirteen points of the cross-sectional area were measured and varied in relative concentration ranging from 0.96 to 1.04. These values were deemed adequate, thus uniform distribution of the lanthanum carrier (and radionuclide additions) was achieved (Griffith et al. July 1976).

VI. TESTING AND VERIFICATION OF THE PHANTOM

In addition to laboratory and material testing, several studies and techniques were used to verify the appropriateness of the Lawrence Livermore National Laboratory torso phantom for emulating the measurement of human subjects. The primary tests included (1) a comparison of the x ray detection efficiencies for ^{103}Pd and plutonium present in the phantom's lungs to the x ray detection efficiencies for inhaled ^{103}Pd (a

mock plutonium) and plutonium, utilizing data from *in vivo* studies recorded prior to the LLNL phantom; (2) a comparison of the x ray detection efficiencies for inhaled ^{92m}Nb to the LLNL phantom, which contained lungs labeled with ^{92m}Nb ; and (3) an intercomparison of organ sets (labeled with a radionuclide) for the second-generation of phantoms. All inhalation experiments were carried out in strict compliance with the review and approval practices in force at the time for all of the participating laboratories human subjects.[†]

To determine the x ray detection efficiencies for ^{103}Pd and plutonium present in the phantom's lungs, known amounts of ^{103}Pd , ^{238}Pu , and a ^{239}Pu mixture containing minor amounts of other plutonium isotopes and 18 ppm ^{241}Am by weight were uniformly added to three sets of phantom lungs. The LLNL realistic torso phantom's measured relative detection efficiency, R , for ^{103}Pd and plutonium was determined using the following ratio (Newton et al. 1981):

$$R = \frac{E_{\text{Pd}}}{E_{\text{Pu}}} = \frac{\text{counts per K x ray emitted by } ^{103}\text{Pd in phantom lungs}}{\text{counts per L x ray emitted by plutonium in phantom lungs}}.$$

The data used to determine the detection efficiency for the LLNL realistic phantom were acquired using a phoswich detector housed in a cadmium-lined lead shield. The photon energy spectra, ranging from 9-keV to 120-keV,

[†]Private communication with Richard V. Griffith, IAEA.

were recorded with the detector suspended in three positions over the phantom, which was placed supine on a horizontal bed. The positions were (1) central; (2) laterally displaced to the left of the central position; and (3) laterally displaced to the right of the central position. Measurements of the phantom were made using the ^{103}Pd , ^{238}Pu , and ^{239}Pu labeled lungs, with each of the phantom's overlays. Repositioning of the phantom in between geometry changes resulted in differences in the detection efficiency by as much as 6% (Newton et al. 1981).

The ^{103}Pd *in vivo* data were acquired by measuring the x ray emissions from the male volunteers using phoswich detectors centrally positioned in a supine position, above the sternum of the supine subject. The Alderson Remab thorax phantom was used as the calibration tool in these earlier studies (Newton, Taylor, and Anderson 1978).

The relative detection efficiency, R , for these early inhalation studies was determined using the following ratio (Newton, Taylor, and Anderson 1978):

$$R = \frac{E_{\text{Pd}}}{E_{\text{Pu}}} = \frac{\text{counts per K x ray emitted by } ^{103}\text{Pd in lungs}}{\text{counts per L x ray emitted by plutonium in lungs}}.$$

Similarities were found between the values of E_{Pd} and E_{Pu} (photon detection efficiencies for palladium and plutonium) indicated by the phantom and those previously recorded for the inhaled ^{103}Pd . The results suggested that the pulmonary distribution of activity in the experimental

subjects was essentially uniform since it was similar to that of the phantom (Newton et al. 1981).

The commercial production of the phantoms led to even more rigorous investigations to establish the phantom's validity. This comprised additional *in vivo* studies involving male volunteers inhaling another nuclide, ^{92m}Nb . Harwell collaborated with four laboratories to assess the accuracy of the production version, manufactured by Humanoid System Inc., of the LLNL realistic phantom: Argonne National Laboratory (ANL), Atomic Weapons Research Establishment (AWRE), Lawrence Livermore National Laboratory, and Battelle Pacific Northwest Laboratory (PNL). Funding for this collaboration was provided by the International Atomic Energy Agency (IAEA). The five participating laboratories, including Harwell, possessed one of the production model phantoms (Newton et al. 1984).

The isotope ^{92m}Nb emits 934-keV gamma-rays, has a half-life of 10.15 days, and decays by electron capture yielding Zr K x rays at 15.8-keV and 17.7-keV. The ^{92m}Nb was produced with Harwell's variable energy cyclotron by alpha irradiation of yttrium. The activity was incorporated into a monodisperse aerosol of 5- μm polystyrene particles and was subsequently administered to volunteers (Newton et al. 1984).

For preparation and use of the ^{92m}Nb -labeled lungs in the phantom, each laboratory had access to one of several pairs of phantom lungs

containing a known amount of ^{92m}Nb . The activity for the lungs was produced at Harwell in the same manner as that intended for labeling particles, and was subsequently sent to LLNL, where a solution of the ^{92m}Nb was standardized by counting the 934-keV gamma-rays from an evaporated aliquot using a GeLi detector. The lungs were fabricated and a measured volume of this solution was added. The same procedure that was used for the addition of transuranic radionuclides was also used for the addition of ^{92m}Nb to the lung set, with one exception. In the ^{92m}Nb lung set, stable niobium in oxalic acid was used as a carrier to achieve uniform labeling rather than the lanthanum nitrate (Newton et al. 1984).

Point sources of LLNL standardized ^{92m}Nb were sent to ANL and to Harwell. Both laboratories measured the gamma-ray emissions from the sources and confirmed LLNL's estimate of the activity to within two percent. This was an important accomplishment since the x ray emission in each subject's lungs to be assumed by all laboratories would depend on ANL's estimates of each subject's pulmonary activity by gamma-ray counting. Conversely, the assumed x ray emissions in the phantom lungs would depend on LLNL's assessment of the activity in the solution used to label them. To verify LLNL's estimates of activity in the phantom lungs, ANL and Harwell counted gamma-rays from the set which each received, using a NaI(Tl) crystal in distant geometry, and compared the count rates with those

from a standardized point source. After appropriate adjustments, based on lung attenuation estimates, both laboratories agreed with LLNL's estimate to within approximately two percent. In using the phantom to determine x ray calibration factors for ^{92m}Nb in lungs, the laboratories focused on reproducing the detector to thorax configurations used with the male volunteers who inhaled ^{92m}Nb -labeled particles (Newton et al. 1984).

The target activity for each volunteer was the deposition of 200 Kbp of ^{92m}Nb in the lungs. Eight male volunteers, who were employees of the five laboratories, inhaled the ^{92m}Nb -labeled aerosol. Each was exposed on separate occasions as part of a five-stage project, which extended over three years. Stage one involved the inhalation of the aerosol and the assessment of the total deposition. Stage two involved the assessment of the clearance time for the aerosol from the ciliated regions and the gut. Stages three and four involved measurements of x ray and gamma-ray emissions at Harwell and each of the participating laboratories. And, stage five involved the continued studies of gamma-ray emissions. The lung depositions were assessed using scintillation detectors. This enabled a subject to be used as a standard to determine the detection efficiency, E_{Nb} (counts per x ray from ^{92m}Nb emitted in lungs), for an individual with a similar physique (Newton et al. 1984).

Use of the phantom to predict x ray detection efficiencies for individual subjects by adding thicknesses of overlays produced a rapid decrease in the

flux of x rays reaching the detectors. This reduction was due to geometrical factors as well as increased attenuation. Because the detectors made contact with the overlays in each case, their separation from the active lungs increased with the thickness of the layer. On occasion, large differences (up to a factor of 2) were noted between the observed and the predicted efficiencies in individual subjects. Factors contributing to these differences comprised, in part, intersubject differences in the relative configurations of detectors, active lungs, and attenuating structures such as the mediastinum and bones. However, when all the data was considered, the ^{92m}Nb inhalation studies showed that the LLNL realistic phantom provided accurate calibration factors for plutonium in lungs (Newton et al. 1984).

Because the physiological structure of women differs from that of men, there were concerns as to whether the phantom would suffice as a calibration standard for women. Therefore, additional *in vivo* studies were performed involving female volunteers inhaling ^{92m}Nb . The activity was produced and administered in the same manner as that for the male subjects. Resulting calibration data also validated the realistic torso phantom for the measurement of female workers.^{††}

The third and final verification consisted of the intercomparison of each organ or organ set of the second-generation of phantoms. Appendix E

^{††}Unpublished document from LLNL's whole-body counter files.

contains comparative organ data for lungs labeled with ^{241}Am , ^{238}Pu and ^{239}Pu . The lung densities and activities were close. Intercomparison measurements qualified the activity loading by measuring each lung set in the core of a specific torso phantom. Calibration factors and dates of calibration were tallied for each set. The calibration factors for all lung sets were also close thus indicating the success of the torso phantom as an intercomparative calibration tool.^{††} These data are reproduced in Tables E.1. through E.3.

VII. SUMMARY

The history pertaining to the developmental criteria and the subsequent fabrication of the first and second-generations of the Lawrence Livermore National Laboratory Realistic Torso Phantom have been described. Data tables and figures have been provided that show the adequacy of the selected tissue substitutes. The studies that were performed to validate the realistic phantom as a calibration tool, for both men and women, were discussed.

Based on the data reviewed, it is apparent that a significant amount of research has been dedicated to the development and use of the LLNL torso phantom thus making it a defacto standard for the calibration of *in vivo* measurement systems. This paper now serves as a basis for understanding the use of the phantom and seeking more detailed information regarding the production of the first and second-generation of phantoms.

VIII. REFERENCES

- Anderson, A.L.; Campbell, G.W.; and Griffith, R.V. In vivo measurement of actinides in the human lung. Livermore, CA: Lawrence Livermore National Laboratory; UCRL 83548; 1979: 103-114.
- Berger, M.J. and Hubbell, J.H. XCOM, Photon cross sections on a personal computer. Washington, DC: U.S. Government Printing Office; Report No. NBSIR 87-3597; 1987.
- Dean, P.N.; Griffith, R.V.; Anderson, A.L. Design criteria for phantoms for calibration of external detectors for the in-vivo assay of plutonium. In: Diagnosis and Treatment of Incorporated Radionuclides, Proceedings of a IAEA and WHO seminar. Vienna: IAEA;IAEA-SR-6/19;1975:265-276.
- Falk, R.B.; Tyree, W.H.; Wood, C.B.; Lagerquist, C.R. A system of high-purity germanium detectors for the detection and measurement of inhaled radionuclides. In: IAEA international symposium on advances in radiation protection monitoring, proceedings of an International Atomic Energy Agency conference. Vienna: IAEA-SM-229/56, 1978.
- Griffith, R.V.; Anderson, A.L.; Dean, P.N. Realistic torso phantom development. Livermore, CA: Lawrence Livermore National Laboratory; Hazards Control Progress Report No. 51, UCRL-50007-75-2; July-December 1975: 3-6.
- Griffith, R.V.; Anderson, A.L.; Dean, P.N. Further realistic torso phantom development. Livermore, CA: Lawrence Livermore National Laboratory; Hazards Control Progress Report No. 52, UCRL 50007-76-1; January-June 1976: 1-5.
- Griffith, R.V.; Anderson, A.L.; Harder, C.A.; Dean, P.N. Continued realistic phantom development. Livermore, CA: Lawrence Livermore National Laboratory; Hazards Control Progress Report No. 53, UCRL-50007-76-2; July-December 1976: 1-3.
- Griffith, R.V.; Fisher, J.C.; Anderson, A.L.; Barry, P.E.; Dean, P.N. Realistic phantom casting. Livermore, CA: Lawrence Livermore National Laboratory; Hazards Control Progress Report No. 54, UCRL-50007-77-1; January-June 1977: 8-10.

- Griffith, R.V.; Dean, P.N.; Anderson, A.L.; Fisher, J.C. Fabrication of a tissue equivalent torso phantom for intercalibration of in-vivo transuranic counting facilities. Livermore, CA: Lawrence Livermore National Laboratory; Preprint: UCRL-80343; 1978: 1-6.
- Griffith, R.V. Polyurethane as a base for a family of tissue equivalent materials. In: Proceedings of the 5th International Congress of the International Radiation Protection Association. Jerusalem, Israel; II: 165-168; 1982.
- Griffith, R.V.; Anderson, A.L.; Sundbeck, C.W.; Alderson, S.W. Fabrication of a set of Realistic torso phantoms for calibration of transuranic nuclide lung counting facilities. International Radiation Protection Association - 6th International Congress - Radiation - Risk - Protection; Berlin, West Germany; Compacts Volume III: 964-967; 1984.
- Griffith, R.V.; Anderson, S.L.; Dean, P.N.; Fisher, J.C.; Sundbeck, C.W. Tissue-equivalent torso phantom for calibration of transuranic nuclide counting facilities. Livermore, CA: Lawrence Livermore National Laboratory; Preprint: UCRL-93776; 1986: 1-13.
- International Commission on Radiation Units and Measurements. Tissue substitutes in radiation dosimetry and measurement. Library of Congress; ICRU Report 44, Table A.1.; 1989: 37-38.
- International Commission on Radiation Units and Measurements. Photon, electron, proton and neutron interaction data for body tissues. Library of Congress; ICRU Report 46, Table A.1.; 1992: 11-13.
- Laurer, G.R. In vivo measurements of radionuclides emitting soft, penetrating radiations. Ph.D. Dissertation. New York University. Available from University Microfilms International, 300 North Zeeb Rd., Ann Arbor, Michigan. 48106. (1968).
- Newton, D.; Taylor, B.T.; Anderson, A.L. X-ray counting efficiencies for plutonium in lungs, derived from studies with inhaled palladium-103. Health Phys. 34:573-585; 1978.
- Newton, D.; White, D.R. Attenuation of 13-20 keV photons in tissue substitutes and their validity for calibration purposes in the assessment of plutonium in lungs. Health Phys. 35:699-703; 1978.

- Newton, D.; Fry, Frances A.; Taylor, B.T.; Eagle, M.C.; Sharma, R.C.
Interlaboratory comparison of techniques for measuring lung burdens
of low-energy photon-emitters. *Health Phys.* 35:751-771; 1978.
- Newton, D.; Campbell, G.W.; Anderson, A.L.; and Fisher, J.C. Consistent
x-ray counting efficiencies for plutonium in lungs, derived by
independent methods. *Health Phys.* 40:748-753; 1981.
- Newton, D.; Wells, A.C.; Mizushita, S.; Toohey, R.E.; Sha, J.Y.; Jones, R.;
Jefferies, S.J.; Palmer, H.E.; Rieksts, G.A.; Anderson, A.L.; Campbell,
G.W. The Livermore phantom as a calibration standard in the
assessment of plutonium in lungs. AERE R 12210; Environmental and
Medical Sciences Division, AERE Harwell, June 1984:1-27.
- Swinth, K.L. Intercalibration for low-energy photon measurements. *Health
Phys.* 25:599-603; 1973.

IX. APPENDIX A: TABLES FOR THE DESIGN CRITERIA FOR
THE LLNL PHANTOM AND PARTICIPATING
LABORATORIES

Table A.1. Dimensional data on “standard man”, laboratory personnel, and the cadaver (Dean et al. 1975).

Parameter	Standard Man	Average Worker	Cadaver
Height	170 cm	177 cm	175 cm
Weight	70 kg	76 kg	76 kg
Chest circumference	—	100 cm	101 cm

Table A.2. Comparative organ volumes (cm³) (Griffith et al. 1986).

Organ	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

^aBased on data from ICRP 23.b

^bA distinction between the left and right kidneys was not made.

Table A.3. Photon emission data from three transuranic isotopes used in the design of the LLNL Phantom^a (Dean et al. 1975).

Isotope	Energy (keV)	Intensity (number/decay)
²³⁸ Pu	"L" x-ray ~ 17	0.115
	γ - rays 43.50	3.4 × 10 ⁻⁴
	99.84	9.4 × 10 ⁻⁵
	152.71	1.0 × 10 ⁻⁵
²³⁹ Pu	"L" x-ray ~ 17	0.00465
	γ - rays ~ 38.7	2 × 10 ⁻⁵
	52.0	7 × 10 ⁻⁵
²⁴¹ Am	"L" x-ray ~ 17	0.376
	26.3	0.025
	43.4	7 × 10 ⁻⁴
	59.5	0.359

^aThese photon emissions do not represent the current values for the isotopes.

Table A.4. Polyurethane formulations for tissue substitutes (Griffith 1980).

Tissue Substitutes	Polyurethane Formulations
LLLM1 (muscle)	95.7% Polyurethane, 4.3% CaCO ₃
LLLM2 (muscle)	66.4% Polyurethane, 25.0% polyethylene, 5.6% CaCO ₃ , 3.0% urea
LLLA1 (adipose)	99.4% Polyurethane, 0.6% acrylic micro-balloons
LLLR1 (rib)	67.0% Polyurethane, 33.0% CaCO ₃
LLLL1 (lung)	96.2% Polyurethane, 3.8% CaCO ₃

Table A.5.a. Elemental compositions and densities for reference tissues.^a

Reference tissues	Density (g/cm ³)	Weight (%)				
		H	C	N	O	Others
Muscle (skeletal)	1.05	10.2	14.3	3.4	71.0	Na-0.1, P-0.2, S-0.3, Cl-0.1, K-0.4
Water	1.00	11.2.0			88.8	
Adipose	0.95	11.4	59.8	0.7	27.8	Na-0.1, S-0.1, Cl-0.1
Cortical Bone	1.92	3.4	15.5	4.2	43.5	Na-0.1, Mg-0.2, P-10.3, S-0.3, Ca-22.5
Lung (deflated)	0.26	10.3	10.5	3.1	74.9	Na-0.2, P-0.2, S-0.3, Cl-0.3, K-0.2

^aThe data were reproduced from Table A.1. in ICRU Report 46, *Photon, Electron, Proton and Neutron Interaction Data for Body Tissues*.

Table A.5.b. Elemental compositions and assumed densities for tissue substitutes.

Tissue Substitutes ^{b,c}	Estimated Density (g/cm ³)	Weight (%)				
		H	C	N	O	Others
LLLM1 (muscle)	1.08	8.96	61.88	3.00	24.37	Ca-1.69
LLLM2 (muscle)	1.05	10.1	65.5	3.22	18.9	Ca-2.24
LLLA1 (adipose)	0.93	9.41	63.98	3.17	23.17	Cl-0.0272
LLLR1 (rib)	1.33	6.32	46.9	2.10	31.5	Ca-13.2
LLLL1 (lung)	0.28	8.9	66.7	3.6	19.3	Ca-1.5

^bUnpublished document from LLNL's whole-body counter files. Letter dated April 18, 1980, from Richard V. Griffith, Leader, Special Projects Division, Hazards Control Department, to Mr. David White, Radiation Physics Department, St. Bartholomew's Hospital, England.

^cThe tissue and electron density adjustments are performed by varying the amount of calcium added to the simulant.

Table A.6. Calculated photoelectric attenuation coefficients for reference tissues and tissue substitutes as a function of photon energy.^a

Photon Energy (MeV)	Photon					Cortical				
	Muscle	Water	LLM1	LLM2	Lung	LLL1	Adipose	LLA1	bone - rib	LLR1
	(cm ² /g)	(cm ² /g)	(cm ² /g)	(cm ² /g)	(cm ² /g)	(cm ² /g)	(cm ² /g)	(cm ² /g)	(cm ² /g)	(cm ² /g)
0.01	4.98	4.94	4.31	4.6	5.08	3.97	2.93	2.75	28	15
0.0136	1.9	1.87	1.68	1.81	1.94	1.55	1.1	1.03	11.5	6.15
0.0172	0.904	0.884	0.813	0.88	0.92	0.746	0.519	0.483	5.76	3.07
0.0202	0.541	0.527	0.492	0.535	0.551	0.451	0.308	0.287	3.57	1.9
0.0228	0.367	0.356	0.337	0.367	0.373	0.308	0.208	0.193	2.48	1.32
0.03	0.151	0.146	0.142	0.155	0.154	0.129	0.0849	0.0785	1.08	0.573
0.04	0.0594	0.0568	0.0566	0.06761	0.0603	0.0517	0.033	0.0304	0.444	0.236
0.05	0.0287	0.0272	0.0277	0.0307	0.0291	0.0252	0.0158	0.0145	0.222	0.118
0.06	0.0158	0.0149	0.0154	0.0171	0.016	0.014	0.00864	0.00793	0.126	0.0666
0.07	0.00951	0.00897	0.00937	0.0105	0.00964	0.00853	0.00518	0.00475	0.0773	0.041
0.08	0.00614	0.00577	0.00609	0.00681	0.00622	0.00554	0.00333	0.00305	0.0507	0.0269
0.09	0.00417	0.00391	0.00416	0.00466	0.00422	0.00379	0.00226	0.00206	0.035	0.0185
0.1	0.00295	0.00276	0.00296	0.00333	0.00299	0.0027	0.00159	0.00146	0.0251	0.0133

^aThe data for the photoelectric coefficients were calculated using the computer program XCOM (Berger and Hubbell 1987).

Table A.7. Second-Generation of phantoms, sixteen participating laboratories.^a

1. Lawrence Livermore National Laboratory
2. Argonne National Laboratory
3. Battelle, Pacific Northwest Laboratory
4. Canada, Radiation Protection Bureau
5. Dounreay nuclear Power
6. AERE Harwell
7. International Atomic Energy Agency
8. Los Alamos National Laboratory
9. Oak Ridge National Laboratory
10. Union Carbide Corporation, Oak Ridge
11. Rocky Flats Plant
12. Environmental Monitoring Systems Laboratory
13. United Kingdom Atomic Energy Authority, Winfrith
14. National radiological Protection Board
15. Savannah River Ecology Laboratory
16. British Nuclear Fuels Limited, Windscale

^aUnpublished document from LLNL's whole-body counter files.

Table A.8. Abbreviations for laboratories.

1. LLNL	Lawrence Livermore National Laboratory
2. ANL	Argonne National Laboratory
3. PNL	Battelle, Pacific Northwest Laboratories
4. RPB	Canada, Radiation Protection Bureau
5. DNP	Dounreay Nuclear Power
6. AERE	AERE Harwell
7. IAEA	International Atomic Energy Agency
8. LANL	Los Alamos National Laboratory
9. ORNL	Oak Ridge National Laboratory
10. Y-12	Union Carbide Corporation, Oak Ridge
11. RFP	Rocky Flats Plant
12. EPA	Environmental Monitoring Systems Laboratory
13. WIN	United Kingdom Atomic Energy Authority, Winfrith
14. NRPB	National Radiological Protection Board
15. SREL	Savannah River Ecology Laboratory
16. BNF	British Nuclear Fuels Limited, Windscale
17. AWRE	Atomic Weapons Research Establishment

X. APPENDIX B: FIGURES

Fig.1. Calculated photoelectric attenuation coefficients for muscle vs. water vs. LLLM1 and LLLM2 (tissue substitutes) as a function of photon energy.

Fig.2. Calculated photoelectric attenuation coefficients for lung (tissue) vs. LLLL1 (tissue substitute) as a function of photon energy.

Fig.3. Calculated photoelectric attenuation coefficients for adipose (tissue) vs. LLLA1 (tissue substitute) as a function of photon energy.

Fig.4. Calculated photoelectric attenuation coefficients for cortical bone - rib vs. LLLR1 (tissue substitute) as a function of photon energy.

Fig.5. Calculated photoelectric attenuation coefficients for reference tissues as a function of photon energy.

XI. APPENDIX C: MEASUREMENT DATA FOR THE
SECOND-GENERATION OF PHANTOMS

Table C.1. Thickness measurements for the torso core.^a

Participating Laboratories	Torso Number	RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	Liver (cm, avg.)
LLNL	C-105P	1.48	1.67	1.56	1.38
ANL	C-109P	1.51	1.56	1.53	1.43
PNL	C-108P	1.56	1.70	1.62	1.50
RPB	C-113P	1.57	1.71	1.64	1.53
DNP	C-119P	1.46	1.60	1.52	1.47
AERE	C-111P	1.49	1.67	1.57	1.52
IAEA	C121	1.50	1.57	1.52	1.34
LANL	C-117P	1.52	1.76	1.62	1.44
ORNL	C-116	1.56	1.68	1.61	1.46
Y-12	C-120	1.42	1.58	1.48	1.41
RFP	C-114P	1.59	1.69	1.64	1.51
EPA	C-104P	1.53	1.56	1.54	1.46
WIN	C-122P	1.49	1.81	1.63	1.55
NRPB	C-118P	1.45	1.69	1.55	1.44
SREL	C-112P	1.47	1.72	1.58	1.39
BNF	C-123	1.33	1.56	1.43	1.29

^aUnpublished data form LLNL's whole-body counter files.

RC = Right chest.

LC = Left chest.

L/R = Left and right.

Table C.2. Liver circle placement for the torso core.^a

Participating laboratories	Torso number	Distance from phantom midline (cm)	Distance from right detector center (cm)
LLNL	C-105P	4.1	20.3
ANL	C-109P	4.1	20.2
PNL	C-108P	4.1	20.3
RPB	C-113P	4.1	20.3
DNP	C-119P	4.1	20.4
AERE	C-111P	4.1	20.1
IAEA	C121	4.1	20.2
LANL	C-117P	4.1	20.2
ORNL	C-116	4.1	20.3
Y-12	C-120	4.1	20.2
RFP	C-114P	4.1	20.1
EPA	C-104P	4.1	20.2
WIN	C-122P	4.1	20.2
NRPB	C-118P	4.1	20.4
SREL	C-112P	4.1	20.1
BNF	C-123	4.0	20.5

^aUnpublished data from LLNL's whole-body counter files.

Table C.3. Lung detector circle distance, 87% fat chest overlays. ^{a,b}

Participating laboratories	overlay number	1st overlay		2nd overlay		3rd overlay		4th overlay	
		(center-center)	(diameter-diameter)	(center-center)	(diameter-diameter)	(center-center)	(diameter-diameter)	(center-center)	(diameter-diameter)
LLNL	A205	16.7	2.7	17.2	3.2	17.7	3.6	17.9	3.9
ANL									
PNL									
RPB	A110	16.7	2.6	17.2	3.1	17.6	3.4	18.1	3.9
DNP									
AERE	A105	16.8	2.65	17.2	3.1	17.5	3.4	18.0	3.3
IAEA	A113	16.7	2.6	17.2	3.1	17.6	3.7	18.1	3.9
LANL									
ORNL									
Y-12									
RFP									
EPA	A106	16.6	2.6	17.2	3.2	17.7	3.6	18.0	3.9
WIN									
NRPB									
SREL	A116	16.7	2.7	17.2	3.2	17.6	3.5	18.0	4.0
BNF	A115	16.7	2.6	17.2	3.1	17.65	3.5	18.2	4.1

^a Unpublished data from LLNL's whole-body counter files.

^b The baseline distance in cm, for the lung detector circles:

1st overlay	16.5–16.7	(center-center)	2.4–2.8	(diameter-diameter)	3rd overlay	17.5–17.7	(center-center)	3.2–3.6	(diameter-diameter)
2nd overlay	17.1–17.3		2.8–3.2		4th overlay	18.7–18.3		3.5–4.0	

Table C.4. Lung detector circle distance, 50% fat chest overlays.^{a,b}

Participating laboratories	overlay number	1st overlay		2nd overlay		3rd overlay		4th overlay	
		(center-center)	(diameter-diameter)	(center-center)	(diameter-diameter)	(center-center)	(diameter-diameter)	(center-center)	(diameter-diameter)
LLNL	B205	16.7	2.6	17.2	3.2	17.7	3.6	18.0	3.9
ANL									
PNL	B121	16.6	2.5	17.2	3.2	17.5	3.6	18.0	4.0
RPB									
DNP	B126	16.7	2.6	17.1	3.1	17.6	3.4	18.0	3.9
AERE	B105	16.6	2.6	17.2	3.1	17.8	3.65	18.1	3.95
IAEA	B119	16.7	2.6	17.2	3.0	17.6	3.4	18.0	3.9
LANL	B117	16.7	2.6	17.3	3.1	17.6	3.4	18.05	3.9
ORNL	B116	16.6	2.5	17.0	2.7	17.5	3.3	18.2	4.1
Y-12	B120	16.6	2.6	17.2	3.2	17.6	3.4	18.0	3.8
RFP	B114	16.7	2.7	17.1	3.1	17.6	3.4	18.2	3.9
EPA									
WIN	B122	16.6	2.6	17.2	3.2	17.5	3.5	18.0	3.9
NRPB	B124	16.7	2.6	17.2	3.1	17.6	3.5	18.0	3.9
SREL	B115	16.7	2.55	17.3	3.2	17.5	3.5	18.1	3.9
BNF	B125	16.6	2.6	17.1	3.0	17.6	3.6	18.1	3.9

^aUnpublished data from LLNL's whole-body counter files.

^bThe baseline distance in cm, for the lung detector circles:

	(center-center)	(diameter-diameter)		(center-center)	(diameter-diameter)
1st overlay	16.5–16.7	2.4–2.8	3rd overlay	17.5–17.7	3.2–3.6
2nd overlay	17.1–17.3	2.8–3.2	4th overlay	18.7–18.3	3.5–4.0

Table C.5. Lung detector circle distance, 100% muscle chest overlays.^{a, b}

Participating laboratories	1st overlay		2nd overlay		3rd overlay		4th overlay	
	overlay number	(center-center)	(diameter-diameter)	(center-center)	(diameter-diameter)	(center-center)	(diameter-diameter)	(center-diameter-diameter)
LLNL	C205	16.6	2.5	17.3	3.2	17.6	3.6	18.1
ANL	C109	16.7	2.6	17.2	3.0	17.6	3.4	18.0
PNL								
RPB	C127	16.7	2.6	17.3	3.3	17.5	3.4	18.0
DNP	C129	16.8	2.7	17.3	3.2	17.6	3.5	18.1
AERE	C116	16.74	2.7	17.2	3.2	17.7	3.6	18.1
IAEA	C130	16.7	2.6	17.2	3.1	17.5	3.4	18.0
LANL	C108	16.7	2.6	17.3	3.4	17.6	3.4	18.1
ORNL								
Y-12								
RFP								
EPA	C125	16.7	2.6	17.2	2.9	17.6	3.5	18.0
WIN	C122	16.7	2.6	17.2	3.1	17.5	3.45	18.05
NRPB	C124	16.7	2.6	17.2	3.0	17.6	3.4	18.0
SREL	C123	16.7	2.6	17.3	3.1	17.6	3.4	18.1
BNF	C132	16.7	2.6	17.3	3.2	17.7	3.6	18.1

^aUnpublished data from LLNL's whole-body counter files.

^bThe baseline distance in cm, for the lung detector circles:

1st overlay	16.5–16.7	2.4–2.8	3rd overlay	17.5–17.7	(diameter-diameter)
2nd overlay	17.1–17.3	2.8–3.2	4th overlay	18.7–18.3	(center-center)

Table C.6. Liver circle placement (vertical distance), 87% fat chest overlays.^a

		1st overlay		2nd overlay		3rd overlay		4th overlay	
Participating laboratories	overlay number	(center–midline)	(center–right lung center)	(center–midline)	(center–right lung center)	(center–midline)	(center–right lung center)	(center–midline)	(center–right lung center)
LLNL	A205	4.2	20.7	4.3	21.0	4.5	21.4	4.5	21.7
ANL									
PNL									
RPB	A110	4.2	20.5	4.3	20.6	4.4	21.5	4.45	21.8
DNP									
AERE	A105	4.2	20.4	4.35	20.8	4.4	21.2	4.5	21.8
IAEA	A113	4.1	20.4	4.3	20.8	4.4	21.2	4.5	21.7
LANL									
ORNL									
Y-12									
RFP									
EPA	A106	4.1	20.5	4.3	20.6	4.4	21.3	4.55	21.7
WIN									
NRPB									
SREL	A116	4.1	20.5	4.35	20.6	4.5	21.2	4.55	21.8
BNF	A115	4.2	20.5	4.3	20.9	4.45	21.4	4.5	21.8

^aUnpublished data from LLNL's whole-body counter files.

Table C.7. Liver circle placement (vertical distance), 50% fat chest overlays.^a

		1st overlay		2nd overlay		3rd overlay		4th overlay	
Participating laboratories	overlay number	(center-midline)	(center-right lung center)	(center-midline)	(center-right lung center)	(center-midline)	(center-right lung center)	(center-midline)	(center-right lung center)
LLNL	B205	4.0	20.3	4.35	20.7	4.5	21.3	4.5	21.6
ANL									
PNL	B121	4.2	20.4	4.3	20.5	4.4	21.3	4.5	21.6
RPB									
DNP	B126	4.1	20.5	4.4	20.7	4.4	21.3	4.5	21.9
AERE	B105	4.1	20.6	4.3	20.7	4.5	21.2	4.5	21.7
IAEA	B119	4.1	20.4	4.35	20.5	4.45	21.2	4.5	21.5
LANL	B117	4.2	20.4	4.4	20.7	4.4	21.2	4.5	21.7
ORNL	B116	4.2	20.2	4.4	20.4	4.5	21.3	4.5	21.4
Y-12	B120	4.2	20.4	4.3	20.6	4.4	21.3	4.5	21.6
RFP	B114	4.2	20.4	4.35	20.6	4.5	21.4	4.5	21.7
EPA									
WIN	B122	4.1	20.5	4.3	20.7	4.4	21.2	4.5	21.7
NRPB	B124	4.2	20.5	4.3	20.7	4.5	21.2	4.5	21.7
SREL	B115	4.3	20.5	4.35	20.6	4.4	21.3	4.5	21.5
BNF	B125	4.1	20.6	4.3	20.7	4.4	21.4	4.6	21.6

^aUnpublished data from LLNL's whole-body counter files.

Table C.8. Liver circle placement (vertical distance), 100% muscle chest overlays.^a

Participating laboratories	overlay number	1st overlay		2nd overlay		3rd overlay		4th overlay	
		(center-midline)	(center-right lung center)	(center-midline)	(center-right lung center)	(center-midline)	(center-right lung center)	(center-midline)	(center-right lung center)
LLNL	C205	4.2	20.5	4.3	20.6	4.4	21.4	4.4	(center to right lung center) 21.7
ANL	C109	4.1	20.4	4.4	20.6	4.5	21.2	4.5	21.6
PNL									
RPB	C127	4.1	20.4	4.35	20.6	4.4	21.3	4.5	21.9
DNP	C129	4.1	20.5	4.35	21.0	4.4	21.3	4.4	21.8
AERE	C116	4.15	20.6	4.35	20.9	4.4	21.3	4.5	21.7
IAEA	C130	4.1	20.4	4.3	20.7	4.4	21.3	4.5	21.7
LANL	C108	4.1	20.4	4.3	20.6	4.4	21.2	4.5	21.7
ORNL									
Y-12									
RFP									
EPA	C125	4.2	20.4	4.4	20.5	4.5	21.1	4.55	21.6
WIN	C122	4.2	20.5	4.3	20.5	4.5	21.4	4.5	21.4
NRPB	C124	4.2	20.5	4.4	20.6	4.5	21.2	4.5	21.6
SREL	C123	4.2	20.4	4.3	20.6	4.5	21.5	4.5	21.6
BNF	C132	4.2	20.5	4.3	20.8	4.4	21.4	4.5	21.8

^aUnpublished data from LLNL's whole-body counter files.

Table C.9. Thickness measurements: 87% fat chest overlays, 1st and 2nd overlays.^a

Participating laboratories	overlay number	1st overlay				2nd overlay			
		RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	Liver (cm, avg.)	RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	Liver
LLNL	A205	0.58	0.56	0.57	0.50	1.13	1.17	1.15	1.04
ANL									
PNL									
RPB	A110	0.68	0.62	0.64	0.71	1.34	1.30	1.32	1.26
DNP									
AEERE	A105	0.69	0.68	0.68	0.70	1.35	1.34	1.34	1.26
IAEA	A113	0.65	0.58	0.61	0.63	1.30	1.27	1.28	1.21
LANL									
ORNL									
Y-12									
RFP									
EPA	A106	0.86	0.82	0.84	0.90	1.52	1.48	1.50	1.46
WIN									
NRPB									
SREL	A116	0.63	0.64	0.63	0.71	1.25	1.23	1.24	1.14
BNF	A115	0.66	0.70	0.68	0.70	1.32	1.29	1.31	1.26

^aUnpublished data from LLNL's whole-body counter files.

RC = Right chest.

LC = Left chest.

L/R = Left and right.

Table C.10. Thickness measurements: 50% fat chest overlays, 1st and 2nd overlays.^a

Participating laboratories	overlay number	1st overlay				2nd overlay			
		RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	Liver	RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	Liver
LLNL	B205	0.60	0.54	0.57	0.44	1.08	1.12	1.10	0.95
ANL									
PNL	B121	0.66	0.62	0.64	0.68	1.24	1.24	1.24	1.16
RPB									
DNP	B126	0.65	0.63	0.64	0.66	1.27	1.22	1.25	1.16
AERE	B105	0.90	0.89	0.89	0.99	1.38	1.45	1.41	1.44
IAEA	B119	0.66	0.63	0.64	0.68	1.32	1.26	1.29	1.19
LANL	B117	0.67	0.64	0.65	0.69	1.27	1.25	1.26	1.70
ORNL	B116	0.55	0.53	0.54	0.63	1.21	1.23	1.22	1.12
Y-12	B120	0.68	0.68	0.68	0.73	1.28	1.24	1.26	1.18
RFP	B114	0.68	0.61	0.64	0.70	1.26	1.21	1.24	1.18
EPA									
WIN	B122	0.66	0.62	0.64	0.69	1.27	1.26	1.26	1.17
NRPB	B124	0.65	0.66	0.65	0.69	1.28	1.25	1.27	1.16
SREL	B115	0.65	0.58	0.61	0.65	1.29	1.23	1.26	1.18
BNF	B125	0.67	0.64	0.65	0.65	1.29	1.26	1.27	1.14

^aUnpublished data from LLNL's whole-body counter files.

RC = Right chest.

LC = Left chest.

L/R = Left and right.

Table C.11. Thickness measurements: 100% muscle chest overlays, 1st and 2nd overlays.^a

Participating laboratories	overlay number	1st overlay				2nd overlay			
		RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	Liver	RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	Liver
LLNL	C205	0.56	0.53	0.54	0.46	1.09	1.14	1.12	0.97
ANL	C109	0.81	0.84	0.83	0.88	1.48	1.48	1.48	1.52
PNL									
RPB	C127	0.67	0.66	0.66	0.69	1.29	1.28	1.28	1.20
DNP	C129	0.63	0.61	0.62	0.66	1.28	1.24	1.26	1.17
AERE	C116	0.69	0.62	0.65	0.73	1.32	1.31	1.31	1.25
IAEA	C130	0.64	0.57	0.60	0.63	1.28	1.21	1.24	1.14
LANL	C108	0.92	0.90	0.91	0.94	1.59	1.56	1.57	1.60
ORNL									
Y-12									
RFP									
EPA	C125	0.66	0.65	0.65	0.69	1.29	1.24	1.27	1.20
WIN	C122	0.73	0.66	0.69	0.73	1.28	1.25	1.26	1.19
NRPB	C124	0.70	0.65	0.67	0.74	1.34	1.31	1.32	1.23
SREL	C123	0.66	0.65	0.65	0.69	1.29	1.28	1.29	1.21
BNF	C132	0.64	0.58	0.61	0.65	1.27	1.22	1.25	1.15

^aUnpublished data from LLNL's whole-body counter files.

RC = Right chest.

LC = Left chest.

L/R = Left and right.

Table C.12. Thickness measurements: 87% fat chest overlays, 3rd and 4th overlays.^a

Participating laboratories	overlay number	3rd overlay			4th overlay				
		RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	Liver	
LLNL	A205	1.65	1.65	1.65	1.60	2.46	2.42	2.44	2.37
ANL									
PNL									
RPB	A110	1.74	1.72	1.73	1.79	2.51	2.42	2.47	2.38
DNP									
AERE	A105	1.83	1.79	1.81	1.89	2.64	2.55	2.60	2.60
IAEA	A113	1.86	1.81	1.83	1.88	2.55	2.49	2.52	2.52
LANL									
ORNL									
Y-12									
RFP									
EPA	A106	2.00	1.89	1.94	2.04	2.74	2.66	2.70	2.73
WIN									
NRPB									
SREL	A116	1.73	1.73	1.73	1.73	2.46	2.39	2.42	2.37
BNF	A115	1.74	1.69	1.71	1.76	2.49	2.42	2.45	2.41

^aUnpublished data from LLNL's whole-body counter files.

RC = Right chest.

LC = Left chest.

L/R = Left and right.

Table C.13. Thickness measurements: 50% fat chest overlays, 3rd and 4th overlays.^a

Participating laboratories	Overlay number	3rd overlay				4th overlay			
		RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	Liver	RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	Liver
LLNL	B205	1.66	1.64	1.65	1.64	2.48	2.44	2.46	2.37
ANL									
PNL	B121	1.76	1.78	1.77	1.77	2.53	2.48	2.51	2.45
RPB									
DNP	B126	1.77	1.75	1.76	1.75	2.50	2.43	2.47	2.40
AERE	B105	1.96	1.90	1.92	2.06	2.72	2.61	2.66	2.73
IAEA	B119	1.74	1.73	1.73	1.77	2.52	2.43	2.48	2.43
LANL	B117	1.74	1.72	1.73	1.76	2.46	2.43	2.45	2.40
ORNL	B116	1.75	1.75	1.75	1.76	2.47	2.42	2.45	2.23
Y-12	B120	1.74	1.74	1.74	1.77	2.56	2.51	2.54	2.46
RFP	B114	1.73	1.72	1.72	1.75	2.54	2.46	2.50	2.48
EPA									
WIN	B122	1.74	1.74	1.74	1.77	2.50	2.42	2.46	2.43
NRPB	B124	1.75	1.73	1.74	1.76	2.51	2.45	2.48	2.43
SREL	B115	1.79	1.77	1.78	1.81	2.51	2.42	2.46	2.40
BNF	B125	1.80	1.75	1.77	1.76	2.54	2.44	2.49	2.41

^aUnpublished data from LLNL's whole-body counter files.

RC = Right chest.

LC = Left chest.

L/R = Left and right.

Table C.14. Thickness measurements: 100% muscle chest overlays, 3rd and 4th overlays.^a

Participating laboratories	Overlay number	3rd overlay				4th overlay			
		RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	Liver (cm, avg.)	RC (cm, avg.)	LC (cm, avg.)	L/R sum (cm, avg.)	Liver
LLNL	C205	1.73	1.71	1.72	1.68	2.45	2.43	2.44	2.38
ANL	C109	2.02	1.94	1.98	2.10	2.71	2.66	2.68	2.75
PNL									
RPB	C127	1.82	1.83	1.82	1.84	2.59	2.53	2.56	2.48
DNP	C129	1.73	1.73	1.73	1.74	2.52	2.42	2.47	2.39
AERE	C116	1.76	1.74	1.75	1.79	2.52	2.44	2.48	2.43
IAEA	C130	1.74	1.68	1.71	1.70	2.49	2.40	2.45	2.35
LANL	C108	1.93	1.91	1.92	2.05	2.74	2.66	2.70	2.72
ORNL									
Y-12									
RFP									
EPA	C125	1.78	1.75	1.76	1.80	2.51	2.47	2.49	2.43
WIN	C122	1.82	1.83	1.82	1.86	2.55	2.56	2.56	2.51
NRPB	C124	1.80	1.79	1.79	1.83	2.56	2.53	2.55	2.49
SREL	C123	1.77	1.78	1.77	1.80	2.53	2.51	2.52	2.43
BNF	C132	1.76	1.70	1.73	1.76	2.48	2.41	2.44	2.39

^aUnpublished data from LLNL's whole-body counter files.

RC = Right chest.

LC = Left chest.

L/R = Left and right.

XII. APPENDIX D: PRELIMINARY CHECKS FOR THE
SECOND-GENERATION OF PHANTOMS

Table D.1. Preliminary checks for the torso cores for the second-generation of phantoms.^a

Visual
Grids or circles smeared?
Blemishes
Air pockets (around ribs, etc.) filled properly?
Inside surfaces smoothed?
Properly marked with identification (both sections)
Lung detector circle distance O.K.? 16.3-16.5 cm (center-center); 2.1-2.4 cm (diameter-diameter)
Red dot grid pattern O.K.?
Are lung circles symmetrically placed around grid pattern?
Is sternum properly placed, and are lung circles tangent? ^b
Liver circle placement O.K.? ____ cm from phantom mid-line. ____ cm from tight detector center.
x-ray transmission measurements on disc sample O.K.?

^aUnpublished data from LLNL's whole-body counter files.

^bInspect x ray.

Table D.2. Preliminary checks for the chest overlays for the second-generation of phantoms.^a

Visual
Grids or circles smeared?
Blemishes?
Properly marked with identification
Lung detector circle distance O.K. (center - center) and (diameter - diameter)
Red dot grid patterns O.K.
Are lung circles symmetrically placed around grid pattern
Liver circle placement (center - midline) and vertical distance (center to right lung center)
Thickness Measurements:
Right chest (cm avg.)
Left chest (cm avg.)
Left + Right (cm avg.)
Liver

^aUnpublished data from LLNL's whole-body counter files.

**XIII. APPENDIX E: COMPARATIVE ORGAN CALIBRATION
DATA FOR THE SECOND-GENERATION OF PHANTOMS**

Table E.1. Comparative organ calibration data for the ^{238}Pu lung sets.^a

Participating laboratories	Torso number	Lung set	Isotope	Left		Right		Calibration factor	Calibration date
				lung density (g/cm ³)	Right lung density (g/cm ³)	Left lung activity (uCi)	lung activity (uCi)		
LLNL	C-105P								
ANL	C-109P	F-107-3	^{238}Pu	0.290	0.297	1.01	1.30	387	2/26/81
PNL	C-108P	526	^{238}Pu	0.317	0.311	1.00	1.25	384	2/26/81
RFB	C-113P								
DNP	C-119P	525	^{238}Pu	0.303	0.301	0.96	1.21	393	2/26/81
AERE	C-111P	F-108-6	^{238}Pu	0.298	0.281	0.99	1.23	387	2/26/81
IAEA	C-121								
LANL	C-117P	504	^{238}Pu	0.298	0.294	0.95	1.17	395	2/26/81
ORNL	C-116	F-107-2	^{238}Pu	0.291	0.285	0.93	1.14	385	2/26/81
Y-12	C-120								
RFP	C-114P	527	^{238}Pu	0.314	0.307	0.99	1.23	376	2/26/81
EPA	C-104P	540	^{238}Pu	0.319	0.314	1.01	1.26	400	2/26/81
WIN	C-122P								
NRPB	C-118P	509	^{238}Pu	0.303	0.300	0.91	1.13	387	2/26/81
SREL	C-112P	528	^{238}Pu	0.312	0.305	0.99	1.22	381	2/26/81
BNF	C-123	524	^{238}Pu	0.309	0.304	0.98	1.22	382	2/26/81

^aUnpublished data from LLNL's whole-body counter files.

Table E.2. Comparative organ calibration data for the ^{239}Pu lung sets.^a

Participating laboratories	Torso number	Lung set	Isotope	Left		Right		Calibration factor	Calibration date
				lung density (g/cm ³)	lung density (g/cm ³)	lung activity (uCi)	lung activity (uCi)		
LLNL	C-105P								
ANL	C-109P	514-A	^{239}Pu	0.312	0.308	2.73	3.54	159.9	3/13/81
PNL	C-108P	513-A	^{239}Pu	0.313	0.31	2.74	3.56	153.8	3/13/81
RPB	C-113P								
DNP	C-119P								
AEERE	C-111P	507	^{239}Pu	0.306	0.295	2.22	2.74	163.3	3/13/81
IAEA	C-121	504	^{239}Pu	0.300	0.281	2.17	2.60	154.8	3/13/81
LANL	C-117P	511-A	^{239}Pu	0.315	0.308	2.75	3.54	156.6	3/13/81
ORNL	C-116								
Y-12	C-120								
RFP	C-114P	510-A	^{239}Pu	0.316	0.309	2.75	3.55	155.2	3/13/81
EPA	C-104P	594	^{239}Pu			2.21	2.96	151.4	3/13/81
WIN	C-122P	530	^{239}Pu	0.312	0.303	2.28	2.86	156.2	3/13/81
NRPB	C-118P	505	^{239}Pu	0.305	0.289	2.2	2.68	161.6	3/13/81
SREL	C-112P	529	^{239}Pu	0.302	0.299	2.21	2.81	160.1	3/13/81
BNF	C-123	531	^{239}Pu	0.311	0.304	2.27	2.89	158.4	3/13/81

^aUnpublished data from LLNL's whole-body counter files.

Table E.3. Comparative organ calibration data for the ^{241}Am lung sets.^a

Participating laboratories	Torso number	Lung set	Isotope	Left		Right		Calibration factor	Calibration date
				lung density (g/cm ³)	lung density (g/cm ³)	lung activity (uCi)	lung activity (uCi)		
LLNL	C-105P								
ANL	C-109P	519	^{241}Am	0.309	0.293	0.28	0.34	37209	3/4/81
PNL	C-108P	516	^{241}Am	0.305	0.297	0.27	0.35	37963	3/4/81
RFB	C-113P								
DNP	C-119P	520	^{241}Am	0.295	0.295	0.26	0.35	37878	3/4/81
AEERE	C-111P	502	^{241}Am	0.312	0.302	0.24	0.30	37973	3/4/81
IAEA	C-121	F-113-11	^{241}Am	0.313	0.298	0.26	0.35	38100	3/4/81
LANL	C-117P	517-A	^{241}Am	0.314	0.306	0.28	0.36	37638	3/4/81
ORNL	C-116								
Y-12	C-120								
RFP	C-114P	501-A	^{241}Am	0.255	0.248	0.23	0.30	37973	3/4/81
EPA	C-104P	518	^{241}Am	0.316	0.288	0.27	0.32	37973	3/4/81
WIN	C-122P	521	^{241}Am	0.308	0.287	0.28	0.34	37938	3/4/81
NRPB	C-118P	503	^{241}Am	0.311	0.295	0.26	0.32	37973	3/4/81
SREL	C-112P	515-A	^{241}Am	0.312	0.307	0.28	0.36	38860	3/4/81
BNF	C-123	F-113-10	^{241}Am	0.299	0.289	0.25	0.33	38153	3/4/81

^aUnpublished data from LLNL's whole-body counter files.