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SCIENTIFIC REPORT

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Wall attenuation and scatter characteristics of ionization chambers at Armed Forces Radiobiology Research Institute

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Ion chambers are used at AFRRI as the primary method of dosimetry. These chambers are calibrated with a cobalt-60 radiation source and are used for dose measurements in high-energy electron, mixed neutron/gamma, and cobalt-60 radiation fields. Radiation attenuation and scattering in the ion chamber wall depends on the radiation field and affects the chamber response. A wall correction factor, K_W, is used to help eliminate this source of error. The wall correction factor was experimentally determined for cobalt-60 and typical AFRRI mixed neutron/gamma fields.

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INTRODUCTION

Ionization chambers have long been the primary method of dosimetry at the Armed Forces Radiobiology Research Institute (AFRRI) (1-8). The determination of absorbed dose from ionization chamber measurements is based on the well-known Bragg-Gray theory (9), which allows mathematical conversion from the ionization produced in a small, gas-filled cavity to the energy absorbed in the medium surrounding the cavity. The direct application of this theory requires that the mass of the gas in the cavity (ionization chamber) be precisely known. In practice, the sensitive volume of an ionization chamber is very difficult to establish; therefore, ionization chambers are usually calibrated in terms of exposure per chamber response in a well-defined gamma-ray field, i.e., roentgens per coulomb (R/C). The chamber response in the field of interest is then converted to dose through the use of various physical parameters (stopping power ratios, mass energy absorption coefficients, etc.) and corrections for the perturbation of the radiation field caused by the chamber. Physical parameters of radiation fields are periodically revised as theory and calculational techniques are improved, whereas most of the corrections relating to the ionization chamber are determined experimentally for each particular chamber.

One necessary chamber correction, the wall correction factor (K_W), has been experimentally evaluated for five different chambers that are used frequently in the various radiation sources at AFRRI. K_W relates the charge collected by an ionization chamber to one that would have been collected if the chamber wall had not been present. The effect of the chamber wall is twofold: (a) Incident radiation is attenuated by the chamber wall, which causes the chamber response to decrease, and (b) the wall also scatters radiation into the sensitive volume, thus increasing the chamber response. In general, attenuation dominates over scatter, and the chamber response decreases with increasing wall thickness.

Although the wall correction can be determined through the use of Monte Carlo calculations (10,11), it is usually determined experimentally by measuring the chamber response as the wall thickness is increased. This report describes the experimental evaluation of the wall attenuation and scatter characteristics of five AFRRI ionization chambers, and discusses the applications to dosimetry in the AFRRI cobalt-60, LINAC, and reactor facilities.

METHODS

The ionization chambers evaluated in this study are listed in Table 1, and the dimensions of each are shown in Appendix A (Tables 3-5, Figures 2-4). Chamber measurements were made with buildup caps of various thicknesses placed on the chamber, and the response was normalized to the response of the chamber for the cap with which transient secondary particle equilibrium had first been established. The chamber response with zero wall thickness was found by extrapolating the graph of response versus wall thickness to zero wall thickness (after electronic equilibrium had been established). The wall correction factor, K_W, was then computed as the ratio of the chamber response at the operating wall thickness to the theoretical response at zero wall thickness.

Table 1. **Ionization Chambers Used in Wall Attenuation and Scatter Study**

Chamber*	Manufacturer	Geometry	Volume (cm^3)	Wall Thickness (cm)
TE 10	AFRRI	Spherical	50	0.72
GR 1A	AFRRI	Spherical	50	0.71
TE 285	Exradin	Cylindrical	0.5	0.10
MG 130	Exradin	Cylindrical	0.5	0.10
TE 155	Exradin	Cylindrical	0.05	0.10

*TE, tissue-equivalent plastic type A-150; GR, graphite; MG, magnesium

For each wall thickness, the chamber response was measured by integrating the ionization charge for a set time interval (between 10 and 30 seconds) while the source was "on." The system noise, or drift, was measured both before and after irradiation of the chamber, and the mean of the pre- and postirradiation drifts was used to compensate the reading, to determine the net ionization current. Measurements were made with the operating potential set at both positive and negative polarity: +/- 1000 volts for the 50-cm^3 chambers, and +/- 500 volts for the 0.5-cm^3 and 0.05-cm^3 chambers.

The cobalt-60 wall attenuation and scatter characteristics were evaluated using the AFRRI Theratron-80 (12) for the 0.5-cm^3 and 0.05-cm^3 tissue-equivalent (TE) chambers. The remaining chambers were evaluated in the National Bureau of Standards cobalt-60 calibration facility. In addition, wall correction factors were determined in the following frequently used fields of the AFRRI TRIGA reactor (13,14):

<u>High-neutron array</u>: A standard 15-cm-lead (Pb) shield was placed in front of the reactor core so that about 90% of the tissue kerma free in air (FIA) was due to the neutron component.

<u>Bare room</u>: No shield was placed between the reactor core and the chambers. In this configuration, the gamma component was about two thirds of the total kerma FIA.

<u>High-gamma array</u>: The reactor was placed 30 cm back in the pool so that the water absorbed almost all the neutrons.

All reactor measurements were performed with the chambers centered 70 cm from the tank wall and 120 cm above the floor. The 50-cm^3 chambers (TE and graphite, GR) and the 0.5-cm^3 chambers (TE and magnesium, MG) were evaluated in all three fields, while the 0.05-cm^3 TE chamber was evaluated only in the array shielded with 15 cm Pb.

An additional measurement was performed using the 0.5-cm^3 chamber to determine the wall correction factor of the AFRRI calorimeter monitor (15) in cobalt-60 and the high-neutron array of the reactor. A mock-up of the calorimeter was constructed using a 2-mm A-150 plastic spherical buildup cap to simulate the core of the calorimeter, and an A-150 plastic cylindrical jacket was placed around the chamber as shown in Figure 1.

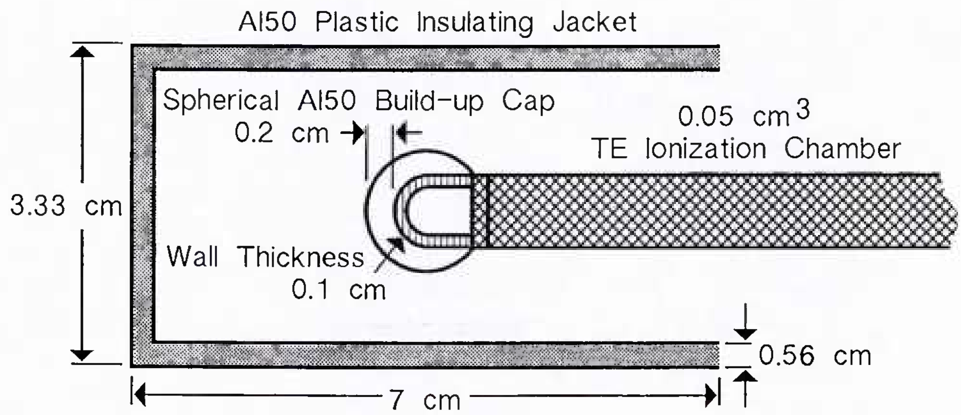

Figure 1. Diagram of calorimeter mock-up

RESULTS

The results of these measurements are displayed in Table 2. In Appendix B, the chamber response is plotted against wall thickness for the chambers in the cobalt-60 and reactor fields. Precision of the ion chamber measurements (indicated by the error bars in Figures 5-14) was about 0.5% for the cobalt-60 measurements, and between 0.5% and 1.5% for the reactor measurements.

Table 2. Wall Attenuation and Scatter Correction Factors

Chamber	Wall Correction Factor: Cobalt-60	Reactor: 15 cm Pb	Reactor: Bare	Reactor: 30 cm water
TE 50 cm^3, No cap	0.977	0.913	0.984	0.993
GR 50 cm^3, No cap	0.978	0.971	0.991	0.991
TE 0.5 cm^3	0.993 2-mm cap	0.986 No cap	0.981 2-mm cap	0.995 4-mm cap
	0.988 (0.983*) 4-mm cap			
MG 0.5 cm^3	0.989 1-mm cap	0.990 No cap	0.970 2-mm cap	0.986 4-mm cap
TE 0.05 cm^3	0.981 (0.989†) 4-mm cap	0.986 No cap		
AFRRI Calorimeter	0.980	0.901		

TE, tissue-equivalent plastic type A-150; GR, graphite; MG, magnesium

*Calculated in reference 11 to be used in AAPM protocol (reference 16)

†Extrapolated from Table III in reference 16

DISCUSSION

The results shown in Table 2 and Appendix B indicate that wall attenuation and scatter characteristics are fairly similar for the three TE chambers, even though the chambers have different geometries. Wall correction data could be used interchangeably for these three chambers with less than 1.5% error in the four fields studied. For example, from the cobalt-60 data of the 50-cm^3 TE chamber, K_W = 0.984 at a 5-cm wall thickness. This compares very well with K_W = 0.988 and K_W = 0.981 measured for the 0.5-cm^3 and 0.05-cm^3 TE chambers, respectively. In cobalt-60 and the high-neutron array of the reactor, the small (0.5 cm^3 and 0.05 cm^3) TE chambers agreed well, and there was also excellent agreement between the small chambers and the large (50 cm^3) TE chambers in the cobalt-60 array and the high-gamma array of the reactor. However, the agreement of the large and small chambers was poorer in the two fields with neutrons present. In Figures 13 and 14, the data show that the response of the 0.05-cm^3 calorimeter mock-up is larger than that expected from a chamber with an 8.6-mm wall thickness. Again, the agreement between the mock-up and the best fit calculations is good in the photon field, but poorer in the neutron field. These data indicate that the scattering in the larger volumes of the 50-cm^3 chamber and calorimeter mock-up is more significant in the neutron fields than in the photon fields. That is, the scattering in these relatively large volumes causes higher readings than expected from the small-chamber data.

Another point of concern, which was not investigated in this work, is the effect of the very large central electrode of the 50-cm^3 chambers. This effect may be especially important when using the 50-cm^3 TE chamber in the neutron fields, because TE materials are very efficient neutron absorbers. Calculations reported in reference 11 show that in cobalt-60, although a larger central electrode will increase the chamber response, it will not have an effect on the wall correction factor. However, similar data in neutron radiation fields are not available. Because the 50-cm^3 chambers are used frequently to measure FIA tissue kerma rates in the various fields of the AFRRI reactor and historically have served as the backbone of reactor dosimetry (1-3), the effect of the large central electrode should be evaluated in future studies.

APPLICATIONS

The application of these wall correction factors are discussed separately for cobalt-60 and LINAC measurements and also for reactor measurements.

HIGH-ENERGY PHOTON AND ELECTRON DOSIMETRY

Dosimetry with ionization chambers in the cobalt-60 and LINAC facilities is based on the American Association of Physicists in Medicine (AAPM) Task Group 21 protocol for High Energy Photon and Electron Dosimetry (16). In this protocol, the chamber wall correction in cobalt-60 must be known to calculate N_{gas}, the dose to the gas in the chamber per electrometer reading.

$$N_{gas} = \frac{N_X \cdot k \cdot (W/e) \cdot A_{ion} \cdot A_{wall} \cdot \beta_{wall}}{\left(\frac{\bar{L}}{\rho}\right)^{wall}_{gas} \cdot \left(\frac{\mu_{en}}{\rho}\right)^{air}_{wall}}$$

where
- N_X = cobalt-60 exposure calibration factor (R/C)
- k = 0.000258 C/kg R
- W/e = quotient of average energy to produce an ion pair by electronic charge = 33.7 J/C for air in cobalt-60
- A_{ion} = saturation correction factor in calibration field
- A_{wall} = wall correction factor in calibration field (K_w)
- β_{wall} = absorbed dose/collision fraction of kerma

$\left(\frac{\bar{L}}{\rho}\right)_{gas}^{wall}$ = ratio of mean restricted stopping powers of wall to gas

$\left(\frac{\mu_{en}}{\rho}\right)_{wall}^{air}$ = ratio of energy absorption coefficient of air to wall

As indicated in Table 2, the values for K_w (same as A_{wall} in AAPM protocol) measured in this study agree well with those calculated for use in the AAPM protocol (11,16).

REACTOR DOSIMETRY

Ionization chamber dosimetry in the mixed neutron and gamma-ray fields of the AFRRI reactor is performed in accordance with established protocols (17-19) and described techniques (20). The cobalt-60 wall correction factors are necessary to determine the absorbed dose calibration factor (α_c), and K_w in the reactor field of interest is needed to determine the FIA tissue kerma from ionization chamber measurements. When making measurements inside phantoms, a wall correction factor for the radiation field is not applied because the chamber wall can be considered as part of the phantom, if the wall and phantom are constructed of similar materials.

The absorbed-dose calibration factor, α_c(Gy/C), is calculated from the exposure calibration factor:

$$\alpha_c = N_X \cdot f_c \cdot K_w \cdot K_i$$

where f_c = 9.62×10^{-3} Gy/R and represents exposure to air tissue absorbed-dose conversion factor for cobalt-60 photons (21)

K_w = wall attenuation and scatter correction factor for the cobalt-60 beam

K_i = other correction factors that may be necessary, such as saturation and polarity

K_w here refers to the wall thickness used during calibration. The suggested wall thickness is the minimum thickness for providing electronic equilibrium, which is about 3 mm and 2 mm for the 0.5-cm^3 TE and MG chambers, respectively.

When performing measurements FIA in the reactor fields, the kerma is determined from the relative chamber response, R', from:

$$R' = R \cdot \alpha_c \cdot K_{tp} \cdot K_i/K_w$$

where α_c(Gy/C) = cobalt-60 tissue absorbed-dose calibration factor

K_{tp} = temperature-pressure correction factor

K_i = other correction factors (polarity, saturation, etc.)

K_w = chamber wall attenuation and scatter correction

Again, the suggested thickness at which K_w is evaluated is the minimum thickness to ensure that electronic equilibrium has been established.

CONCLUSIONS

Wall correction factors have been evaluated for five different chambers in cobalt-60 and in three reactor radiation fields. These factors are applied to ionization chamber measurements to determine the absorbed dose or FIA tissue kerma rates in the cobalt-60 gamma-ray fields, LINAC electron and bremsstrahlung fields, and the mixed neutron and gamma-ray fields of the AFRRI reactor. In addition, the wall correction for the newly constructed AFRRI calorimeter has been determined in cobalt-60 and the high-neutron array of the AFRRI reactor.

APPENDIX A. CHAMBER SPECIFICATIONS

Table 3. 50-cm^3 Spherical Chamber Specifications

Outer Diameter: 6.43 cm

Inner Diameter: 4.99 cm

Diameter of Central Electrode: 3.0 cm

Buildup Caps:

Chamber	Number of Buildup Caps on Chamber	Wall Thickness (cm)
TE (A-150 plastic)	None	0.721
	1	1.021
	2	1.335
	3	1.649
GR (graphite)	None	0.714
	1	1.033
	2	1.347
	3	1.660

Table 4. 0.5-cm^3 Cylindrical Chamber Specifications

Outer Diameter: 1.14 cm

Inner Diameter: 0.94 cm

Diameter of Central Electrode: 0.46 cm

Height of Central Electrode: 0.87 cm

Inner Height of Sensitive Volume: 1.41 cm

Buildup Caps

Nominal thickness:	0.1	0.2	0.3	0.4	0.5	0.6
Measured thickness:						
TE (A-150 plastic)	—	0.200	0.300	0.399	0.499	0.601
MG (magnesium)	0.100	0.200	0.300	0.396	0.500	0.601

Table 5. 0.05-cm^3 Cylindrical Chamber Specifications

Outer Diameter: 0.56 cm

Inner Diameter: 0.36 cm

Diameter of Central Electrode: 0.16 cm

Height of Central Electrode: 0.7 cm

Inner Height of Sensitive Volume: 0.8 cm

Buildup Caps

Nominal thickness:	0.3	0.4	0.4	0.500	0.6	1.00
Measured thickness:						
TE (A-150 plastic)	0.30	0.380	0.410	0.500	0.630	1.00

Calorimeter mock-up: Spherical cap (A-150 plastic), 0.2 cm diameter; Jacket (A-150 plastic), 0.56 cm wall thickness, 3.33 cm outer diameter, 7.00 cm outer height

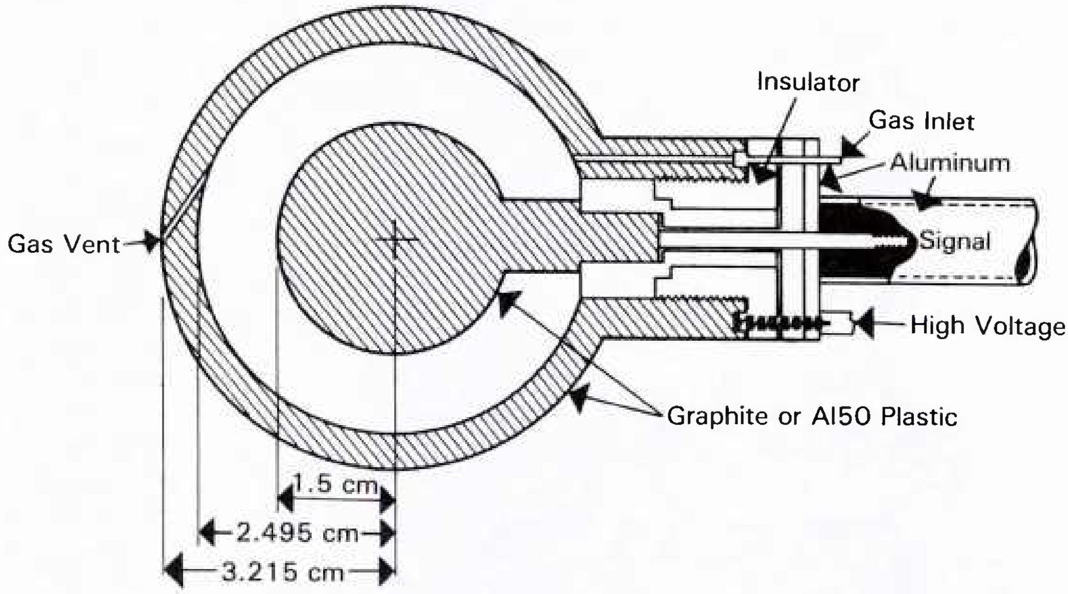

Figure 2. Diagram of 50-cm^3 chamber

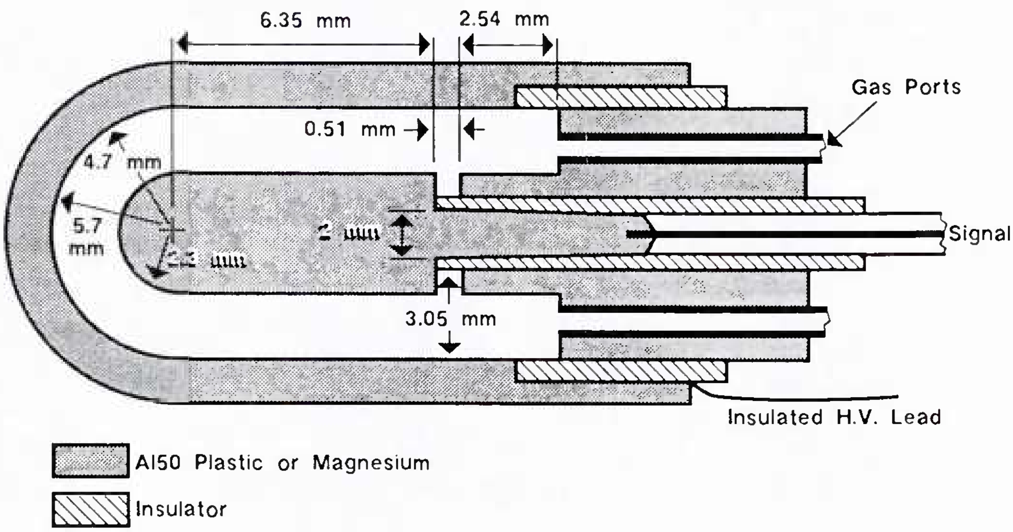

Figure 3. Diagram of 0.5-cm^3 chamber

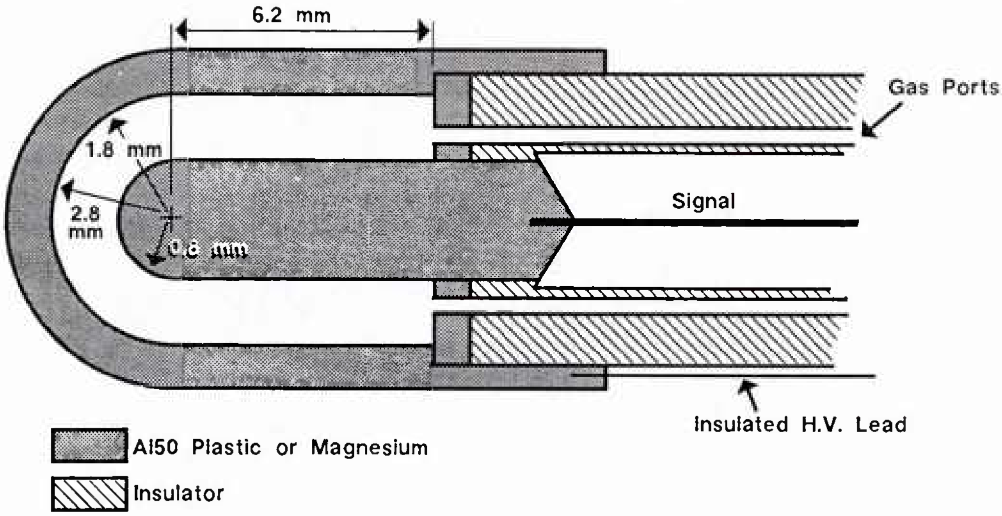

Figure 4. Diagram of 0.05-cm^3 chamber

APPENDIX B. WALL ATTENUATION AND SCATTER DATA

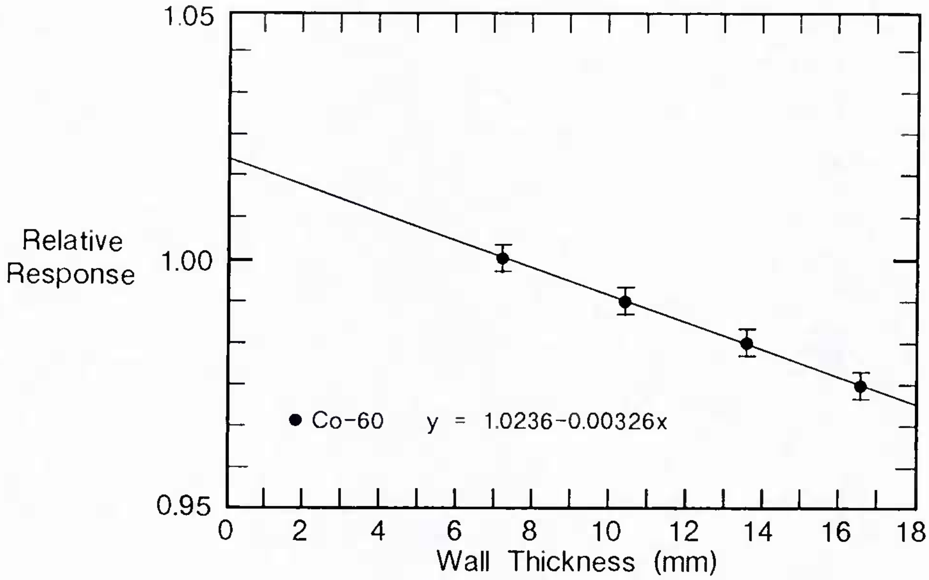

Figure 5. TE 50-cm^3 wall attenuation and scatter in cobalt-60 fields

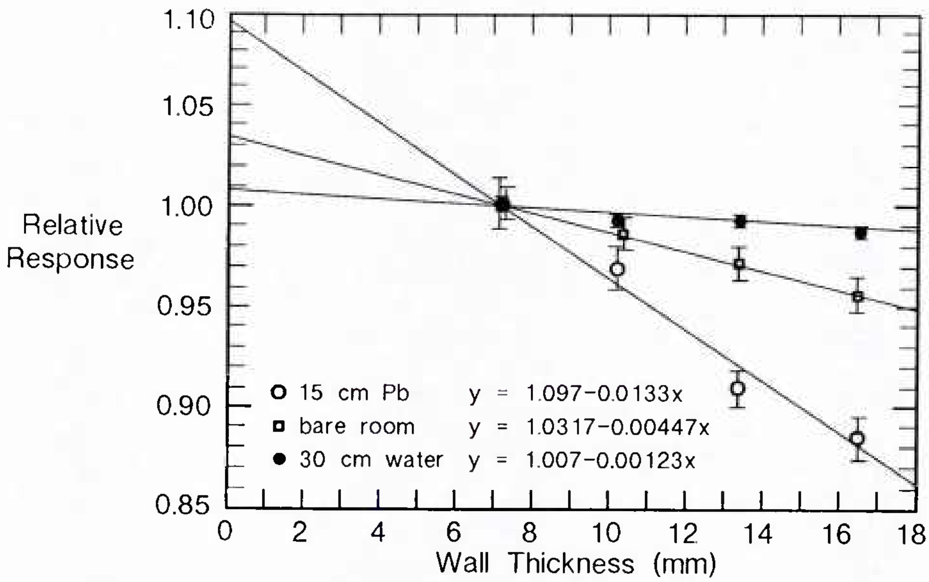

Figure 6. TE 50-cm^3 wall attenuation and scatter in reactor fields

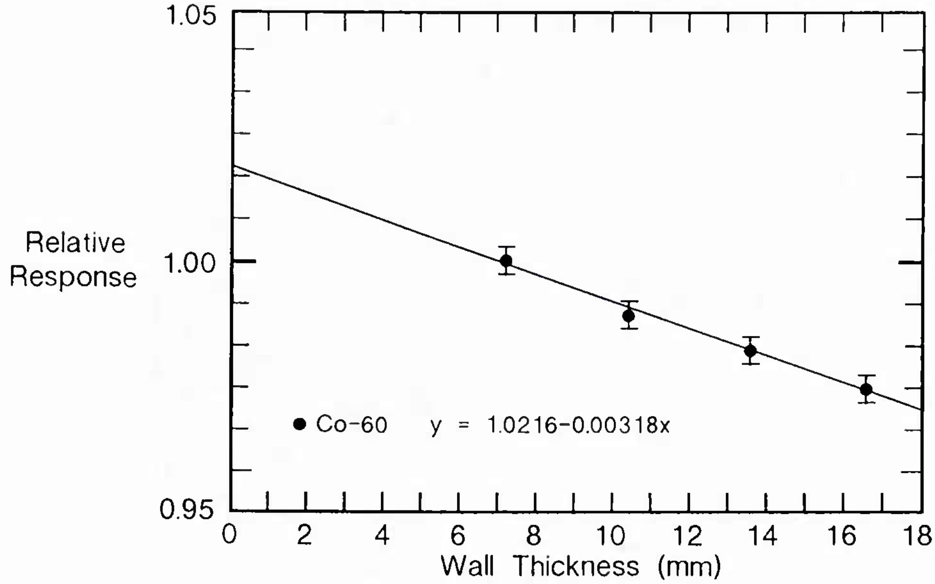

Figure 7. Graphite 50-cm^3 wall attenuation and scatter in cobalt-60 fields

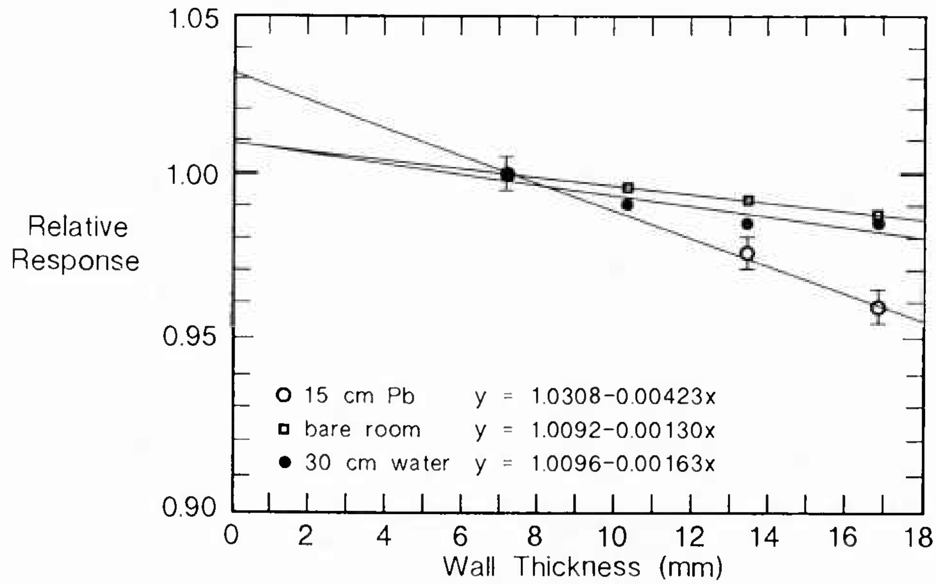

Figure 8. Graphite 50-cm^3 wall attenuation and scatter in reactor fields

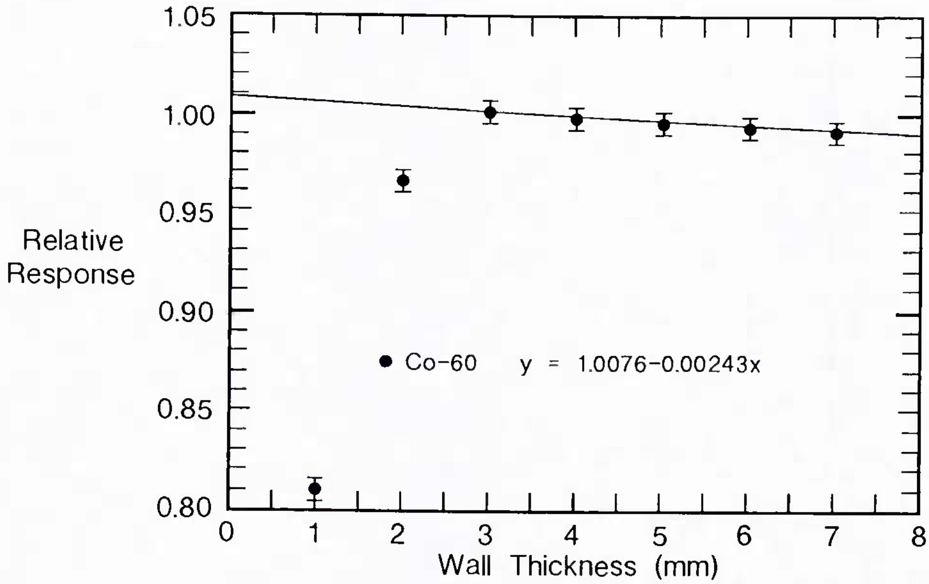

Figure 9. TE 0.5-cm^3 wall attenuation and scatter in cobalt-60 fields

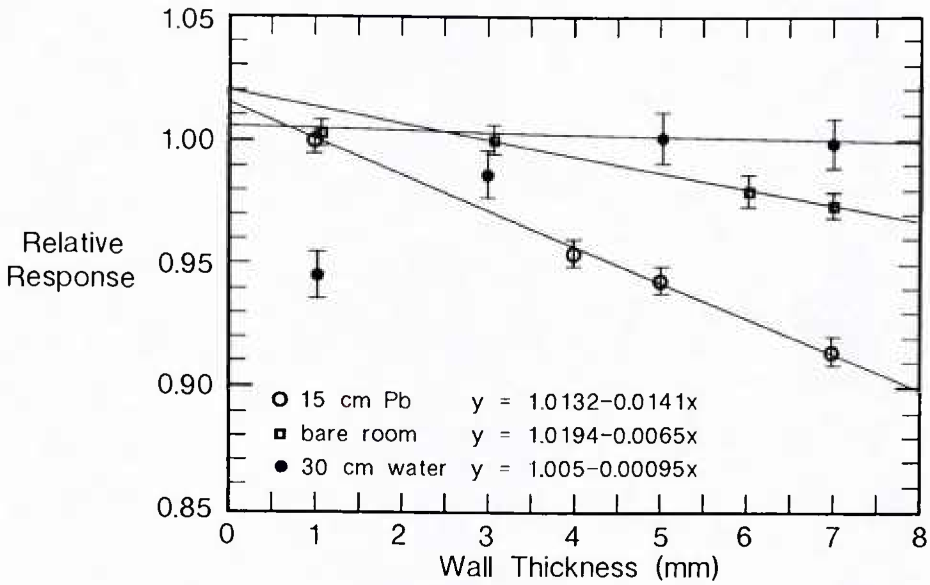

Figure 10. TE 0.5-cm^3 wall attenuation and scatter in reactor fields

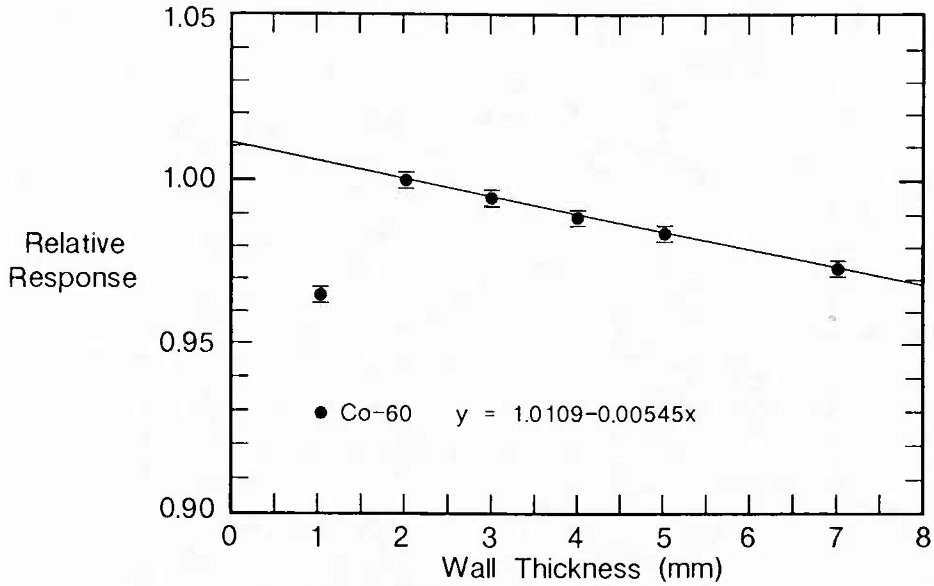

Figure 11. MG 0.5-cm^3 wall attenuation and scatter in cobalt-60 fields

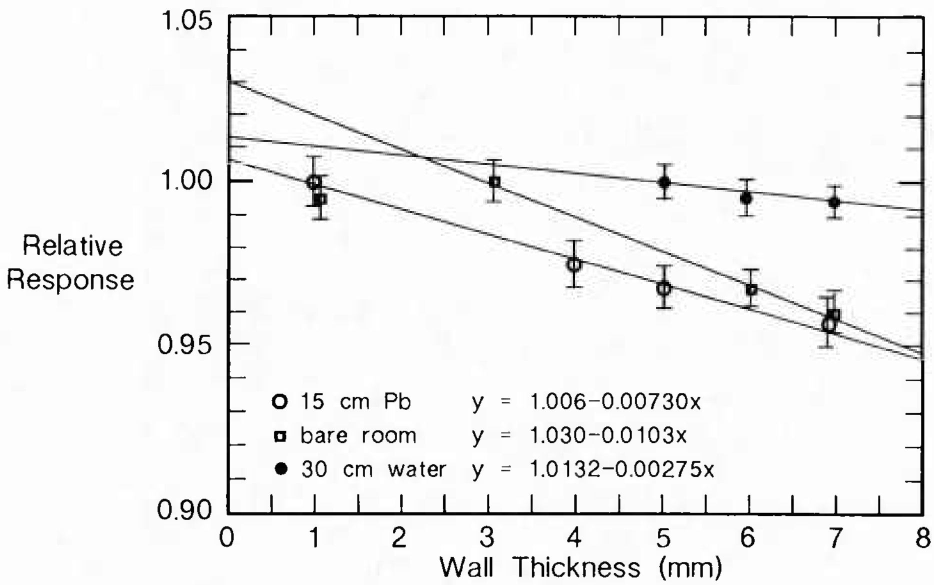

Figure 12. MG 0.5-cm^3 wall attenuation and scatter in reactor fields

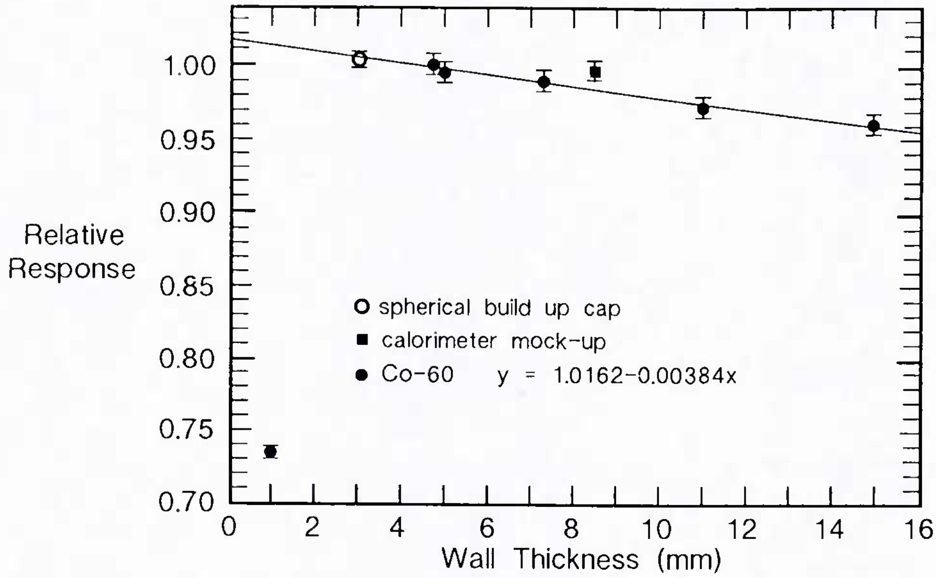

Figure 13. TE 0.05-cm^3 wall attenuation and scatter in cobalt-60 fields

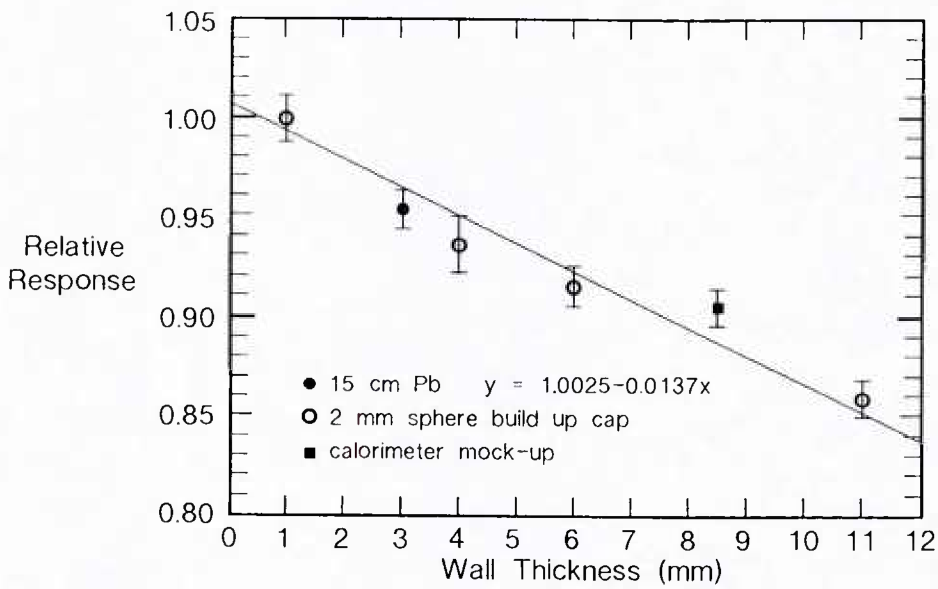

Figure 14. TE 0.05-cm^3 wall attenuation and scatter in reactor fields

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