Accuracy of EGSnrc calculations at ^{60}Co energies for the response of ion chambers configured with various wall materials and cavity dimensions

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In this investigation, five experimental data sets are used to evaluate the ability of the EGSnrc Monte Carlo code to calculate the change in chamber response associated with changes in wall material and cavity dimension at ^{60}Co energies. Calculations of the ratios of response per unit mass of air as a function of cavity volume for walls ranging from polystyrene to lead are generally within 1%–3% of experiments. A few exceptions, which are discussed, include 20%–30% discrepancies with experiments involving lead-walled chambers used by Attix *et al.* [J. Res. Natl. Bur. Stand. **60**, 235–243 (1958)] and Cormack and Johns [Radiat. Res. **1**, 133–157 (1954)], and 5% discrepancies for the graphite chamber of Attix *et al.* (relative to data for other wall materials). Simulations of the experiment by Whyte [Radiat. Res. **6**, 371–379 (1957)], which varied cavity air pressure in a large cylindrical chamber, are generally within 0.5% (wall/electrode materials ranging from beryllium to copper). In all cases, the agreement between measurements and EGSnrc calculations is much better when the response as a function of cavity height or air pressure is considered for each wall material individually. High-precision measurements [Burns *et al.*, Phys. Med. Biol. **52**, 7125–7135 (2007)] of the response per unit mass as a function of cavity height for a graphite chamber are also accurately reproduced, and validate previous tests of the transport mechanics of EGSnrc. Based on the general agreement found in this work between corresponding experimental results and EGSnrc calculations it can be concluded that EGSnrc can reliably be used to calculate changes in response with changes in various wall materials and cavity dimensions at ^{60}Co energies within a accuracy of a few percent or less.
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I. INTRODUCTION

In the mid-to-late 1950s and early 1960s, several experiments[1–7] were performed with the aim of investigating the effects of cavity size and wall material on the measured charge or current per unit mass of gas in the cavity (herein referred to as response) for chambers free in air. Experiments focused on ^{60}Co beams, but other photon sources were also tested, including ^{137}Cs, ^{198}Au, betatron radiation, and orthovoltage x rays. Contrary to the predictions of the Bragg–Gray (BG) cavity theory, it was observed that the response varies with changes in cavity height (distance between front and back wall of a plane-parallel chamber) or cavity air pressure to an extent that roughly correlates with the disparity between the respective atomic numbers of the wall and cavity gas.[4–7] At the time, interest in these experiments was driven, in part, by the cavity theory introduced by Spencer and Attix (SA) in 1955,[8] which had the potential to predict the above-mentioned variation since it was formulated to explicitly account for the production of δ rays and, hence, take into account the cavity size dependence of chamber response.

Although it was found that SA cavity theory could predict some of the variation in response with changes in cavity dimension, which at the time was regarded as a significant improvement over BG cavity theory, some discrepancies with measurements were still observed that are large by present standards [e.g., discrepancies as much as 10% in ^{60}Co beams[3,4] and 20% for a lead chamber in ^{198}Au beams[3]]. However, ignoring those few large discrepancies, the response predicted by SA cavity theory was often within a few percent of measured values for a range of wall materials. Unfortunately, since these early comparisons were not concerned with achieving a high level of precision, uncertainties on the measured values were rarely discussed. Yet despite the challenges involved with experiments of this type,[9] it is reasonable to assume that the measurements were, on average, reproducible to within a few percent or less. This is comparable to the level of uncertainty on the cross sections[10,11] and stopping powers[12] used in modern Monte Carlo codes such as EGSnrc,[13,14] which are estimated to be within 1%–2% at ^{60}Co energies. Thus, in addition to early tests of cavity theory, these experiments are also well suited to test the cross sections in EGSnrc via calculations of the change in response associated with changes in wall material, at least at the level of experimental precision. Previously, the EGSnrc Monte Carlo code was evaluated for its ability to calculate the ratio of responses of chambers with different walls,[15,16] but only a few comparisons are made with experiment. The primary aim of this investigation is to test the EGSnrc code more thoroughly by comparing with a broad range of measurements in ^{60}Co beams. In particular, the EGSnrc code will be

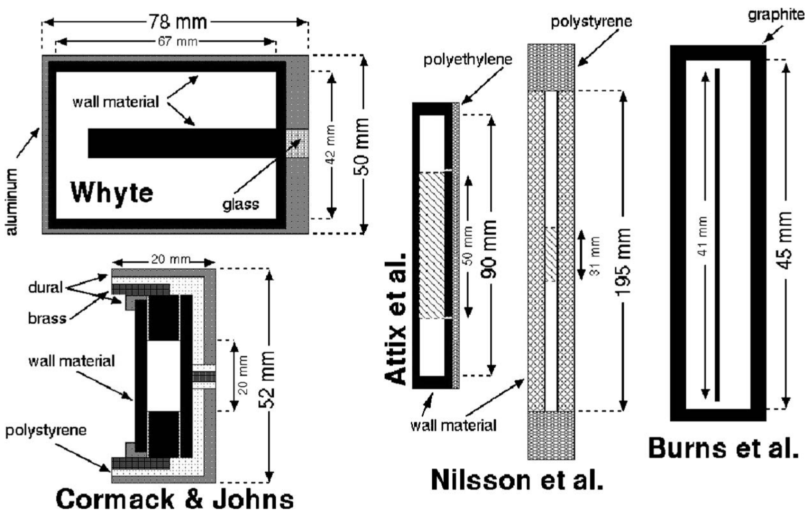

FIG. 1. Schematic diagrams of the five ion chambers investigated in this study as modeled with EGSnrc using the CAVRZnrc user code (Ref. 27). An outer layer of Lucite ($0.19\ \mathrm{g/cm^2}$) was used to support the front wall of the Attix *et al.* chamber when lead walls were used (not shown). The inner lining of the walls in the Nilsson *et al.* chamber was coated with $0.88\ \mathrm{mg/cm^2}$ mylar foils (not shown), one of which was aluminized (back wall/collector) and the other coated with graphite. Sensitive regions of the Attix *et al.* and Nilsson *et al.* chambers are indicated. All the chambers are shown as they were oriented in experiments to detect a fluence of photons incident from the left. Diagrams are not drawn to scale.

evaluated using the NIST XCOM photon cross sections[17–19] and electron stopping powers with ICRU density corrections.[12]

In addition to the above-mentioned test of cross sections, simulations of these experiments also present the opportunity to test the transport mechanics of EGSnrc through calculations of the response as a function of cavity height or cavity air pressure. Past analysis of the transport mechanics using the Fano cavity test for photons from 10 keV to 1.25 MeV have shown that EGSnrc is accurate to within 0.1% with respect to its own cross sections and geometry descriptions for chambers made with graphite, aluminum, and copper.[20–22] In this investigation, the Fano test was repeated for lead at ^{60}Co energies in order to supplement perspective on the results of tests performed via comparisons with experiment. These comparisons with experiment will, at best, only test the transport mechanics at the level of experimental precision, which is assumed to be $\approx 1\%$ in most cases. However, recent high-precision measurements (standard uncertainty of $\approx 0.015\%$) by Burns *et al.*[9] of the response to ^{60}Co as a function of cavity volume were also simulated for the opportunity to better confirm the accuracy of the transport algorithms for graphite wall materials.

II. METHODS AND CALCULATIONS

II.A. Experimental data

The majority of experiments of the type discussed earlier were concisely summarized in a paper by Burlin,[4] who later contributed additional experiments and discussion in a series of papers on the topic.[4–7] Unfortunately, the discussion of his own experiments did not include some important information about the chamber wall thicknesses required for Monte Carlo calculations. However, papers by Attix *et al.*,[3] Whyte,[2] and Cormack and Johns[23] contain most of the information needed for calculations. Additional measurements of the same type by Nilsson *et al.*,[24] intended for an investigation into perturbation effects, were also simulated. Combined, these experiments provide a comprehensive set of ^{60}Co data covering various chamber geometries and wall materials. In a more recent paper, Burns *et al.*[9] reported high-precision measurements but only for a graphite chamber.[9] Based on information in the original papers, schematic diagrams of the chambers used in the above-mentioned studies are shown in Fig. 1 as they were modeled in this investigation using EGSnrc. Additional details of each experiment are discussed in the following sections.

II.A.1. Experimental data of Nilsson et al.

As part of an investigation into perturbation effects, Nilsson *et al.*[24] used a custom-made, cylindrically symmetric plane-parallel ionization chamber (Fig. 1) to record, among other things, the response as a function of cavity height in a ^{60}Co beam. The results of interest to our investigation are presented in Fig. 5 of their paper.[24] Measurements were obtained for the chamber configured with either polystyrene (C_8H_8), aluminum, or lead as a backscatter material (back wall, about $0.5\ \mathrm{g/cm^2}$ thick), and a slab of polystyrene used as a build-up material (front wall, about $0.5\ \mathrm{g/cm^2}$ thick to provide full buildup). The cavity height was taken to be equal to the thickness of ring-shaped spacers placed between the front and back wall which, according to the diagram provided by the authors, had an inner diameter larger than the collimated beam. By determining the cavity height this way, the authors reported an uncertainty in the cavity height of about 0.02 mm, which results in a 2% uncertainty in chamber response at a cavity height of 1 mm. They also reported an uncertainty in the cavity height associated with the bending of the mylar foils (which line the inside of both walls) induced by the applied potential. The potential was adjusted to maintain a constant electric field strength at all cavity heights. Therefore, the walls/liner were likely distorted to the same extent at each cavity height, and reduced the cavity volume relatively more at smaller cavity heights. The effect of this bending was not accounted for in the measurements since, as the authors explain, doubling the potential resulted in only a 1% decrease in the relative response at a cavity height of 1 mm (which could result from a 0.01 mm distortion). However, these small distortions have a much larger effect at smaller cavity heights, and the implications of not accounting for the effect on the measured response are discussed in Sec. IV A.

In addition to the measurements discussed above, the response as a function of the atomic number of backscatter material was also reported for build-up materials of polystyrene, aluminum, and lead, and these results were compared to Monte Carlo calculations using the EGS4 Monte Carlo code[25] (from Fig. 7 of their paper). It is assumed that these measurements were performed with a cavity height of 1 mm.

Since the aim of these experiments was to investigate perturbation effects, and since their interest was to make comparisons with Monte Carlo calculations in some cases, no corrections for attenuation and scatter were reported for any of their measurements.

II.A.2. Experimental data of Whyte

Experiments by Whyte,[2] published in 1957, varied the cavity air pressure rather than the chamber cavity height. However, both methods have the effect of changing the average path length in air (in g/cm^2) that an electron must travel to cross the cavity, and so in SA cavity theory varying air pressure is equivalent to changing the cavity dimension. In this experiment, a large air-tight cylindrical ionization chamber made of aluminum was used (Fig. 1). The chamber could be fitted with an inner liner and central electrode ($\approx$1 cm diameter) made of any desired material. The air pressure in the cavity was controlled by a pump connected directly to the cavity, and the chamber was oriented with its electrode pointed toward a 1.1 TBq ^{60}Co source placed 30 cm away (see Fig. 1). The relative measurements of response were corrected for the effects of attenuation and scatter by the wall and aluminum liner by adding sheaths of wall material of known thicknesses to the *outside* of the chamber (i.e., outside the aluminum liner) and measuring the resulting reduction in ionization current. The correction, denoted here by $K_{\mathrm{wall}}^{\mathrm{expt}}$, was taken as the ratio of the response corresponding to zero wall thickness (determined from a linear extrapolation) with the response corresponding to the nominal thickness, which was not reported but inferred from the schematic diagram provided in the paper. It was assumed that no additional corrections for the mean center of electron production (K_{cep}) were applied to the measurements since it was not mentioned in his paper. Section II D. discusses how these results were "reverse corrected" in order to be compared with our EGSnrc calculations since the corrections Whyte used were not reported. The original results of this experiment are from Fig. 4 of his paper[2] for wall and electrode materials of beryllium, graphite, aluminum, and copper.

II.A.3. Experimental data of Attix et al.

In 1958, Attix *et al.*[3] measured the response of a large cylindrically symmetric plane-parallel ion chamber (Fig. 1) to a filtered ^{60}Co beam as a function of cavity height. The 37 GBq ^{60}Co source was filtered by 12 mm of lead, 2.4 mm of tin, 0.5 mm of copper, and 0.8 mm of aluminum, presumably in that order, to attenuate the low-energy portion of the spectrum as much as possible. The authors report a 1 m source-to-chamber distance (SCD) for measurements with x rays, but the low activity of the ^{60}Co source coupled with heavy filtration likely required a shorter SCD (e.g., between 10 and 30 cm) in order to produce the 10^{-12} A currents they wished to measure. This is discussed further in Sec. IV B. Wall materials of graphite, aluminum, copper, tin, and lead were used and the thicknesses of each were reported. Each back wall was supported on a 0.17 g/cm^2 thick layer of polyethylene, and the front wall of the lead chamber was supported by a 0.19 g/cm^2 thick layer of Lucite™. Measurements were obtained with and without ring-shaped spacers separating the chamber walls. These spacers, which were made of the same material as the walls, had a diameter small enough to sit within the irradiated field, but had an inner diameter large enough to leave a 2 cm thick guard ring of air around the 5 cm diameter sensitive region. Cavity heights were determined by measuring the capacitance of the walls for the given applied potential, which had the advantage, particularly for thinner high-Z wall materials, of accounting for any distortions of the walls due to the applied potential, and subsequently reducing the uncertainty in the measured cavity volume. Corrections for the effects of attenuation and scatter were applied to the final measurements using measured values of $K_{\mathrm{wall}}^{\mathrm{expt}}$ determined using the same procedure employed by Whyte[2] discussed earlier. As such, the original measurements, from Fig. 10 of their paper[3] for a ^{60}Co beam, had to be reverse corrected (refer to Sec. II D) in order to make comparisons with EGSnrc calculations. It was assumed that no K_{cep} corrections were applied to the measured values.

II.A.4. Experimental data of Cormack and Johns

The earliest experimental data investigated in this study were published by Cormack and Johns[23] in 1954. Similar to Attix *et al.*[3] and Nilsson *et al.*,[24] their experiment made use of a cylindrically symmetric plane-parallel ionization chamber with interchangeable front and back walls. Measurements of the relative ionization current as a function of cavity height resulting from a 111 TBq ^{60}Co source (80 cm SCD)[40] were recorded for wall materials of graphite, aluminum, copper, silver, and lead. The thicknesses required to provide full buildup were determined from the maximum response obtained from measurements of ionization as a function of wall thickness (using a different chamber similar in design and a 4×4 cm^2 field size). As in the Nilsson *et al.* experiment, the cavity height was inferred from the thickness of ring-shaped spacers made of the same material as the wall, and which were within the 10×10 cm^2 field. Measurements were repeated for the graphite and lead chambers without the use of spacers, but how the cavity height was determined in this experiment was not discussed. No wall corrections ($K_{\mathrm{wall}}^{\mathrm{exp}}$) were mentioned and so it is assumed they were not used. The results used for comparison with EGSnrc are from Fig. 5 of their paper.[23]

II.A.5. Experimental data of Burns et al.

The most recent set of experiments investigated here was reported by Burns *et al.*[9] in 2007. The goal of their experiment was to derive the air-kerma rate in a ^{60}Co beam from a differential measure of the ionization current with respect to cavity volume using a variable-volume graphite plane-parallel chamber (Fig. 1). Obtaining the air-kerma rate this way is, in principle, more accurate since the measures of cavity volume are considered differentially. When configured with the smallest cavity height, the chamber used is geometrically similar to the BIPM primary standard. Information on the dimensions and material densities are reported in their paper. For their experiments, cavity heights were varied from 5.15 to 10.13 mm and the cavity volume in each configuration was precisely determined before and after each measurement using a three-dimensional coordinate measuring machine. Independent measurements of the ionization were repeated at least three times for five cavity heights (i.e., the chamber was disassembled and reassembled between measurements), and the standard uncertainty on the repeated measurements was typically 1.5 parts in 10^4. Experimentally derived corrections for the effects of ion recombination and diffusion, stem scatter, the presence of inhomogeneous materials, and chamber orientation were applied in all cases. Measurements were also corrected for the effects of beam axial nonuniformity (K_{an}) and attenuation and scatter by the walls (K_{wall}) using correction factors calculated with the PENELOPE Monte Carlo code. Details about the calculated correction factors are discussed in their paper as well as in an earlier paper by Burns.[26] For comparisons with the EGSnrc calculations in the present paper, the final measured results, from Fig. 3 of their paper,[9] were divided by their reported K_{wall} and K_{an} values, and normalized by the response of the BIPM standard (also with K_{wall} and K_{an} corrections removed).

II.B. EGSnrc calculations of chamber response

All of the ion chambers used in the experiments discussed above are cylindrically symmetric, and so the geometries of each were modeled as shown in Fig. 1 using the CAVRZnrc user code.[27] The only notable approximation made to the geometry descriptions was for the Whyte chamber,[2] where the electrode was modeled as a perfect cylinder rather than with the hemispherical end as shown in his paper. The effect of this approximation was confirmed to be negligible via calculations with a more accurate geometry (for copper walls at 1 atm) modeled with the EGSnrc C++ class library in the cavity user code. The thicknesses of the walls used in the calculations for each of the chambers are listed in Table I.

TABLE I. Thicknesses of chamber walls used in EGSnrc models. Wall thicknesses for the Nilsson *et al.* (Ref. 24), Attix *et al.* (Ref. 3), and Burns *et al.* (Ref. 9) chambers were specified in their papers (without uncertainties). The wall thicknesses used by Cormack and Johns were determined from measured build-up curves provided in their paper (Ref. 23). Dimensions for the Whyte chamber were inferred from the schematic diagram he provided (Ref. 2).

Chamber	Wall material	Thickness (g/cm^2)
Nilsson *et al.*	Polystyrene	0.5
(0.5 g/cm^2 polystyrene	Aluminum	0.5
buildup)	Lead	0.5
Whyte	Beryllium	0.449
	Graphite[a]	0.413
	Aluminum	0.657
	Copper	2.177
Attix *et al.*	Graphite[a]	0.308
	Aluminum	0.437
	Copper	0.925
	Tin	0.770
	Lead	0.873
Cormack and Johns	Graphite[a]	0.399
	Aluminum	0.415
	Copper	0.353
	Silver	0.343
	Lead	0.354
Burns *et al.*	Graphite[b]	0.534

[a]Density assumed to be 1.7 g/cm^3.
[b]Density assumed to be 1.84 g/cm^3.

In all cases, the calculated ion chamber response was assumed to be directly proportional to the calculated dose to the cavity, D_{cav}. Since descriptions of the ^{60}Co sources and enclosures were not given in enough detail to model the sources in the Monte Carlo simulations, a ^{60}Co spectrum calculated by Mora *et al.*[28] was used as an input in the form of a collimated, isotropic point source in all cases except for the Attix *et al.*[3] experiment. Input spectra for the latter simulation were calculated using FLURZnrc,[27] which scored the photon fluence in a 0.1 cm thick vacuum layer (5 cm in diameter) due to a point source with the Mora *et al.* ^{60}Co spectrum filtered as described in Sec. II A 3. The scatter component from the filter is included in the spectra computed in this way. This process was repeated for SCDs of 8, 10, 15, 30, 50, 80, and 100 cm since it was not reported which SCD was used for ^{60}Co measurements. Simulations of the Attix *et al.* chamber were also performed using a phase space from a BEAMnrc (Ref. 29) simulation as an input to investigate the effect of electron contamination, which explains some discrepancies between EGSnrc calculations and measurements (see Secs. III D and IV B).

For simulations of experiments involving changes in the cavity air pressure (Whyte experiment), separate interaction cross-section data sets were created (for convenience) for each air density corresponding to the measured pressure, as was done in previous Monte Carlo calculations of this type.[30,31] For comparisons with the Cormack and Johns data, which reported measured ionization currents rather than response, EGSnrc calculations of D_{cav} were multiplied by the cavity mass. In all cases, the calculated results were normalized to the experimental data via multiplication by a factor a such that $\Sigma(e_i - ac_i)^2$ is minimized, where e_i and c_i are the ith experimental and corresponding EGSnrc-calculated values, respectively. It can be shown that $a = \Sigma e_i c_i / \Sigma c_i^2$. The root mean squared deviation (RMSD) of a data set is given by $\sqrt{\Sigma(e_i - ac_i)^2 / n}$.

II.B.1. EGSnrc parameters

EGSnrc transport parameters were selected to account for atomic relaxations, spin effects, and the binding energies of electrons in Compton scattering. All calculations made use of XCOM photon cross sections[17–19] and electron interaction cross sections which include the density effect corrections from ICRU Report 37.[12] For simulations of the Burns *et al.* experiment, the correction for the density effect in the stopping power data for graphite with a density of 1.84 g/cm^3 was approximated by the ICRU density corrections corresponding to a density of 1.7 g/cm^3 using a mean excitation energy (I value) of 78 eV. Buckley *et al.*[16] have shown that using a density of 2.265 g/cm^3 to compute the density effect corrections reduces the chamber response by less than 0.2% for the particular chamber geometry they were investigating. That same study showed that changing the I value from 78 to 87 eV increased the response of a graphite chamber by 1.2%. However, it was unclear from that investigation which I value is more appropriate. A more recent report by Wang and Rogers[32] suggests that a higher I value for graphite should be used. In this investigation, the ICRU-recommended I value of 78 eV is used for graphite.

In any EGSnrc calculation, the user must select the cut-off energy (ECUT) below which charged particles are no longer tracked, and also provide a set of stopping powers *restricted* to collisional energy losses below a threshold value (AE) which is $\leqslant$ECUT. Using larger values of ECUT reduces CPU time, and it is therefore desirable to know the highest value of ECUT that one can use without loss of accuracy. It has previously been shown that it is sufficient to use AE =ECUT=521 keV (511 keV rest mass+kinetic energy) for graphite chambers and ^{60}Co energies.[33] Mainegra-Hing *et al.*,[34] however, showed lower values should be used for chambers with small cavities, and it is unclear which value should be used for chambers made with nonair-equivalent, high-Z materials. Figure 2 shows some examples of EGSnrc-calculated values of D_{cav} as a function of ECUT for chambers made with graphite and lead, where AE=ECUT in all cases. An ECUT value of 1 keV is the de facto lower limit in EGSnrc, and is used for the most accurate calculations even though the stopping powers, which are calculated according to the Bethe–Block formalism, are known to be inaccurate for high-Z materials (since AE should be $\geqslant$K-shell binding energies).[35]

In Fig. 2, it can be seen that an ECUT value of 10 keV is suitable for graphite chambers since it yields the same response, within statistics, as calculated with ECUT=1 keV. Above 10 keV, calculated responses begin to diverge for the Attix *et al.* chamber (0.5 mm cavity height). The results for the Cormack and Johns chamber (2.6 mm cavity height) begin to diverge above 20 keV, suggesting that smaller cavity heights are more sensitive to ECUT values. The figure for lead chambers shows that the sensitivity to ECUT is also dependent on the geometry and wall material. The response of the Cormack and Johns chamber with lead walls and a cavity height of 0.7 mm calculated with an ECUT of 10 keV was more than 5% below the response calculated with an ECUT of 1 keV, even though the cavity height is comparable to the graphite Attix *et al.* chamber discussed earlier. Calculations of the Nilsson *et al.* chamber with a similar cavity height show that simply replacing the front wall with polystyrene and adding a guard ring dramatically reduces the sensitivity of the calculated response to ECUT. Additional calculations of this type for the Whyte chamber with copper walls showed that D_{cav} was roughly constant for ECUT $\leqslant$10 keV. D_{cav} was also constant for the Cormack and Johns chamber with silver walls and a 1 mm cavity height for ECUT $\leqslant$2 keV.

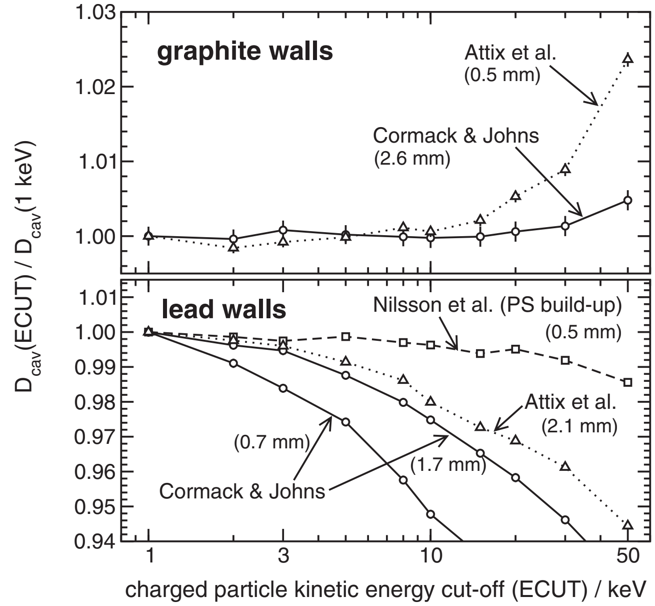

FIG. 2. EGSnrc calculations of chamber response as a function of the cut-off for the lowest kinetic energy of charged particles created (AE) and tracked (ECUT), where AE=ECUT in all cases, for two of the chambers with graphite walls and three chambers with lead walls. The Nilsson *et al.* chamber had a polystyrene front wall rather than a lead wall (see Sec. II A 1). The dimension labels (in millimeters) represent the cavity height of the chamber. Statistical uncertainties on the data for the lead chamber are smaller than the symbols ($\leqslant$0.15%).

To avoid artifacts caused by prematurely terminating particle histories, photons and charged particles were tracked down to a kinetic energy of 1 keV (i.e., ECUT=PCUT =1 keV) in all calculations. Range rejection of charged particles was used as a time-saving option, where the tracking of charged particles was terminated if their range was too short to reach the cavity. It was confirmed that this had a negligible impact on the results.

II.C. Fano cavity test for a lead-walled ion chamber

Since part of this investigation relies on the transport mechanics within EGSnrc for calculating the response of lead ion chambers, previous benchmarks of the transport mechanics based on the Fano cavity test for graphite, aluminum, and copper wall materials[20,21] are extended here to include lead. The Fano cavity test is described in detail elsewhere,[21,22] but essentially involves verifying that for a chamber with full build-up walls,

$$\frac{D_{\mathrm{cav}}K_{\mathrm{wall}}}{\bar{E}\left(\frac{\bar{\mu}_{\mathrm{en}}}{\rho}\right)_{\mathrm{wall}}} = 1, \tag{1}$$

where $D_{\mathrm{cav}}K_{\mathrm{wall}}$ is the dose to the cavity filled with wall gas per incident fluence corrected for the effects of attenuation and scatter, and $\bar{E}(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{wall}}$ is the collision kerma of the wall per incident fluence. To satisfy the Fano cavity conditions, the differences in the density effect between the stopping powers for the lead wall ($11.35\ \mathrm{g/cm^3}$) and the lead gas in the cavity ($0.001205\ \mathrm{g/cm^3}$) were removed by using the same density effect corrections for each density (corresponding to the bulk density). Thus, the cross sections and stopping powers are the same per $\mathrm{g/cm^2}$ in both the wall and cavity. The CAVRZnrc user code[27] was used with photon regeneration to calculate $D_{\mathrm{cav}}K_{\mathrm{wall}}$ for the incident Mora *et al.*[28] ^{60}Co spectrum and the g user code was used to calculate $\bar{E}(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{wall}}$. Both calculations used the same cross-section data sets and thus this test is not sensitive to the uncertainties in the cross sections, only the internal consistency of the transport algorithms.

II.D. Calculated K_{wall} corrections

Since the response of an ion chamber is proportional to the product of the stopping-power ratio and $(\bar{\mu}_{\mathrm{en}}/\rho)^{\mathrm{air}}_{\mathrm{wall}}$ after correction for effects such as wall attenuation and scatter, Attix *et al.*[3] and Whyte[2] corrected measurements of chamber response for the effects of attenuation and scatter using measured K_{wall} correction factors, denoted here as $K^{\mathrm{expt}}_{\mathrm{wall}}$. The goal of the present study was to compare the chamber responses without these corrections but, unfortunately, the respective $K^{\mathrm{expt}}_{\mathrm{wall}}$ corrections used were not reported in either of these studies. It is assumed here that the $K^{\mathrm{expt}}_{\mathrm{wall}}$ corrections are equivalent to the response of the chamber divided by the response measured when the thickness of the walls was doubled. The present authors thus determined the values of $K^{\mathrm{expt}}_{\mathrm{wall}}$ using calculated responses. Determining the corrections in this way, although the common practice at the time, has since been shown to be inaccurate in a series of papers.[36–38] These same studies demonstrated that accurate values are given by Monte Carlo methods as implemented in CAVRZnrc.[27] Table II lists the present authors' calculated $K^{\mathrm{expt}}_{\mathrm{wall}}$ corrections for the Whyte and Attix *et al.* chambers along with the corresponding correct values calculated by CAVRZnrc. The calculated $K^{\mathrm{expt}}_{\mathrm{wall}}$ values for the Attix *et al.* chamber are consistent with their remarks that the corrections were a few percent. The uncertainties on $K^{\mathrm{expt}}_{\mathrm{wall}}$ values for the Attix *et al.* tin and lead chambers are higher due to the larger relative uncertainties on the calculations of chamber response from which these values are derived. The experimental results without these corrections are referred to as reverse-corrected responses.

TABLE II. EGSnrc-calculated values of $K^{\mathrm{expt}}_{\mathrm{wall}}$ and $K^{\mathrm{EGSnrc}}_{\mathrm{wall}}$ corrections for the chambers used by Whyte (Ref. 2) and Attix *et al.* (Ref. 3). Corrections are calculated as discussed in the text. Values for the Whyte chamber correspond to an atmospheric air pressure within the cavity, whereas the values for the Attix *et al.* chamber are the average over all cavity heights. $K^{\mathrm{EGSnrc}}_{\mathrm{wall}}$ values for the Attix *et al.* chamber are less than unity since they are dominated by scatter corrections that are large due to the contribution to response of photons scattered from outside the sensitive volume. The numbers in parentheses represent the 1σ uncertainty on the last digit for each reported value.

	Whyte		Attix *et al.* (10 cm SCD)	
Wall	$K^{\mathrm{expt}}_{\mathrm{wall}}$	$K^{\mathrm{EGSnrc}}_{\mathrm{wall}}$	$K^{\mathrm{expt}}_{\mathrm{wall}}$	$K^{\mathrm{EGSnrc}}_{\mathrm{wall}}$
Be	1.0162(5)	1.0315(3)	⋯	⋯
Graphite	1.0142(4)	1.0347(3)	1.0022(3)	0.9918(1)
Al	1.0206(7)	1.0472(5)	1.0034(7)	0.9920(6)
Cu	1.0645(8)	1.0934(7)	1.0074(3)	0.9767(1)
Sn	⋯	⋯	1.013(4)	0.9512(2)
Pb	⋯	⋯	1.032(4)	0.9114(5)

III. RESULTS

III.A. Fano cavity test for a lead-walled ion chamber

EGSnrc calculations of $D_{\mathrm{cav}}K_{\mathrm{wall}}/[\bar{E}(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{wall}}]$ discussed in Sec. II C yielded a value of 1.0013 ± 0.0004. The internal consistency of the EGSnrc algorithms has thus been verified to within about 0.13% for lead wall materials at ^{60}Co energies. This is only slightly worse than for lower-Z walls where a 0.1% consistency was obtained.[20,21]

III.B. Nilsson *et al.* chamber

Measurements and EGSnrc calculations of the response as a function of cavity height for the plane-parallel chamber used by Nilsson *et al.*[24] are shown in Fig. 3. Included in Fig. 3 are the experimental data as they were originally presented along with the same data corrected for a possible systematic error in the cavity volume associated with the inward bending of the wall due to the applied potential (see Sec. II A 1). As with the original measured data, the corrected experimental results were normalized relative to the response of the polystyrene (C_8H_8) chamber at a cavity height of 1 mm. The cavity heights used for the corrected experimental data were reduced by 0.01 mm for the polystyrene back wall, 0.02 mm for the aluminum back wall, and 0.03 mm for the lead back wall, chosen arbitrarily to give the best fit with calculated results. It can be seen that a 0.03 mm reduction in the cavity height increased the measured response by 6% at a cavity height of 0.5 mm for the lead chamber. Normalized collectively to the corrected experimental results, the RMSD of EGSnrc calculations from experiment, expressed as a fraction of the experimental value for each wall material and cavity height, is 1.4%. The average RMSD for each wall material normalized independently is also 1.4%.

Figure 4 shows comparisons between their measurements and EGS4 calculations of chamber response as a function of backscatter material with the EGSnrc calculations in the present study (using a 1 mm cavity height and assuming no

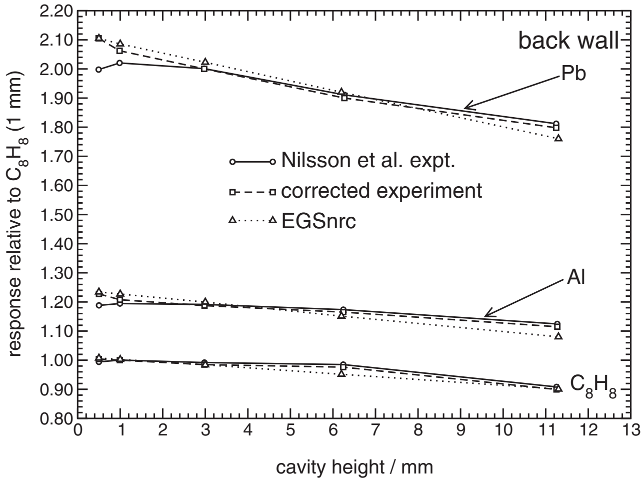

FIG. 3. Measured and EGSnrc-calculated response as a function of cavity height for the plane-parallel ion chamber used by Nilsson *et al.* (Ref. 24). The front wall is made of polystyrene (C_8H_8) in all cases. The dashed lines represent experimental data corrected for the possibility of small reduction in the cavity height due to the applied potential between the front and back wall (details discussed in the text). EGSnrc results are normalized to the corrected results as discussed in Sec. II B. Statistical uncertainties on the EGSnrc results are 0.2% or less, and the experimental measurements were reported to be reproducible to within 0.8% (1σ).

bending of the walls). Three build-up materials (polystyrene, aluminum, and lead) were investigated. For the extreme case of a lead backscatter material, calculations using EGS4 underestimated the experimental response by as much as 8% for a lead build-up material. The largest discrepancy using EGSnrc is 3%, and the RMSD is 1.4%.

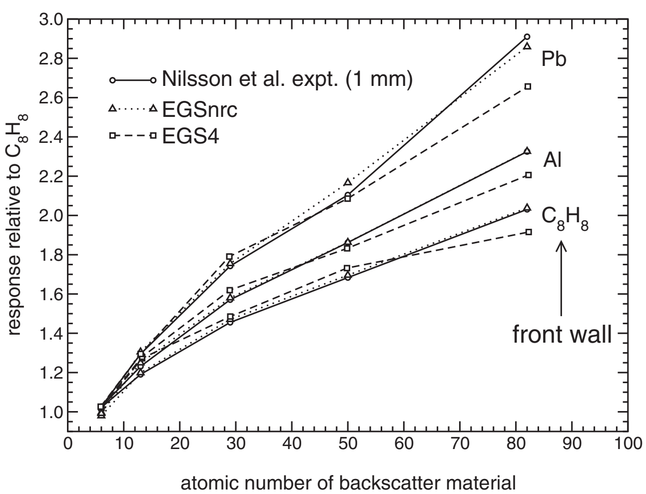

FIG. 4. Measured and EGS4/EGSnrc-calculated responses as a function of the atomic number of the back wall material for the plane-parallel chamber investigated by Nilsson *et al.* (Ref. 24). Results are shown for polystyrene (C_8H_8), aluminum, and lead used as build-up materials. A 1 mm cavity height was assumed for the calculations, which were normalized to the measured data as discussed in Sec. II B. Measurements and EGS4 calculations appear as they were originally presented (Ref. 24). Statistical uncertainties on the EGSnrc calculations are 0.2% or less, and the experimental measurements were reported to be reproducible to within 0.8% (1σ). Statistical uncertainties on the EGS4 calculations were better than 1%.

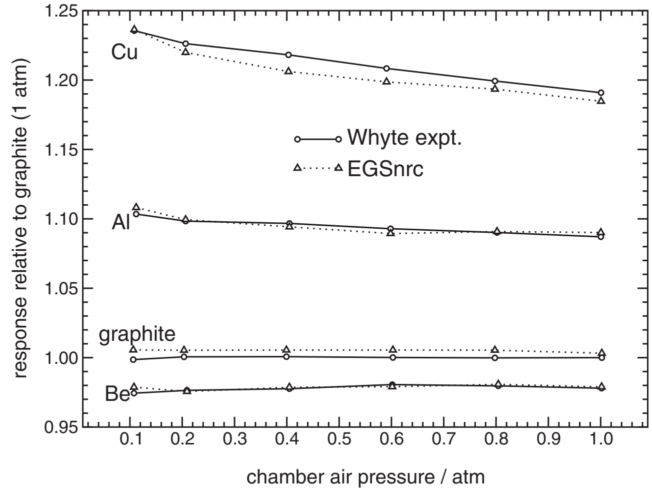

FIG. 5. Measured (reverse corrected, Sec. II D) and EGSnrc-calculated response as a function of cavity air pressure for the cylindrical ion chamber used by Whyte (Ref. 2). The experimental results are normalized to the response of the graphite chamber at 1 atm. Statistical uncertainties on the calculated responses are 0.2% or less. Experimental uncertainties were not reported.

III.C. Whyte chamber

Figure 5 shows the measured (reverse corrected, see Sec. II D) and EGSnrc-calculated response for the chamber used by Whyte[2] as a function of cavity air pressure. The RMSD of the EGSnrc calculations, normalized collectively to all the experimental results, is 0.5%. The RMSD is within 0.3% if the calculated and measured data sets are normalized separately for each wall material.

III.D. Attix *et al.* chamber

The measured (reverse corrected, see Sec. II D) and EGSnrc-calculated response as a function of cavity height for the Attix *et al.* plane-parallel chamber with spacer rings are shown in Fig. 6. The EGSnrc results were calculated with an SCD of 10 cm, and are normalized with respect to the measured data for aluminum, copper, and tin. The normalized results calculated for these three materials are generally within 2% of measurements (RMSD of 1.3%), with a maximum discrepancy of 3% (tin chamber, 10.3 mm cavity height). For the graphite and lead chambers, the relative calculated responses are as much as 9% below and 17% above measurements, respectively. Figure 7 shows the same comparison for the chambers without spacers. As in Fig. 6, the calculations were normalized with respect to the measured data for aluminum, copper, and tin, and the RMSD for these three materials is approximately 1%. Discrepancies for the graphite and lead data are as large as for the chambers with spacers. If the absolute discrepancies observed with these chambers in Figs. 6 and 7 are ignored, then the relative agreement as a function of cavity height for a given wall material is within 2% (RMSD of approximately 1%).

The above-discussed calculations were repeated for SCDs ranging between 8 and 100 cm. At 8 cm, the normalized calculations were comparable to the results for an SCD of

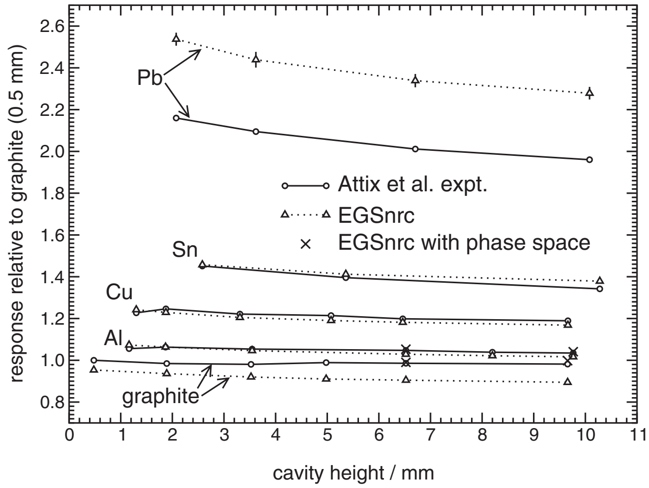

FIG. 6. Measured (reverse corrected, Sec. II D) and EGSnrc-calculated response for the plane-parallel chamber used by Attix *et al.* (Ref. 3) as a function of cavity height. Measured data are normalized to the response for the graphite chamber at the smallest cavity height. EGSnrc results for aluminum, copper, and tin wall materials are normalized collectively to the respective experimental results as discussed in Sec. II B. Statistical uncertainties on the calculated responses are 0.2% or less. Experimental uncertainties were not reported.

10 cm. For an SCD of 15 cm and greater, the calculated values of $K_{\mathrm{wall}}^{\mathrm{expt}}$ for the copper and tin chambers were less than unity since calculated responses increase with added wall thickness. Despite this, calculated responses as a function of cavity height for each wall material normalized independently to the respective measurements were generally within 2%, even at an SCD of 100 cm. Furthermore, the calculated response for each wall material relative to graphite at this SCD was comparable to those calculated for an SCD of 10 cm for all wall materials except tin, which was about 5% higher.

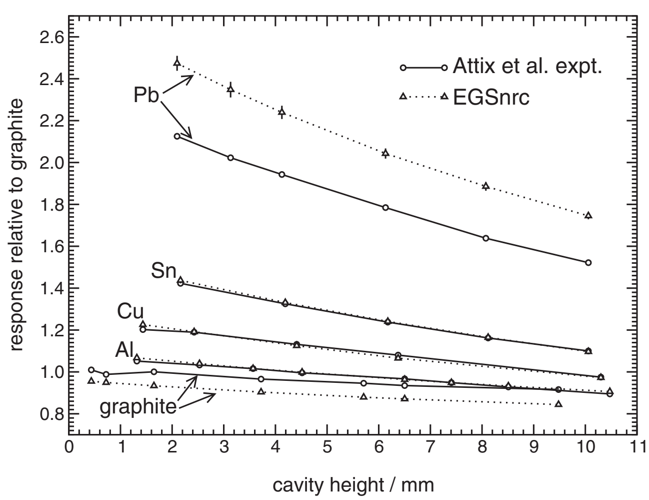

FIG. 7. As in Fig. 6 for the chamber without ring-shaped spacers as used by Attix *et al.* (Ref. 3). The reverse-corrected experimental results are normalized relative to the results in Fig. 6 since they were originally presented on the same graph (Ref. 3).

Calculations were also repeated with the unfiltered Mora *et al.* ^{60}Co spectrum[28] and with 1.25 MeV photons, and compared with reverse-corrected measurements using corresponding $K_{\mathrm{wall}}^{\mathrm{expt}}$ values. In both cases, the agreement between experiment and calculations were comparable to the results for the filtered beam case for the graphite, aluminum, and copper chambers (with calculations for the graphite chamber relative to the aluminum and copper chambers ≈10% below the measurements). For the Mora spectrum incident on the tin and lead chambers, the calculated response relative to the other three chambers increased by 10% and 15%, respectively, which increases the discrepancy with experiment. For the monoenergetic 1.25 MeV photons, the respective responses of the tin and lead chambers relative to the other chambers decreased by 5% and 14%. Although the agreement for the lead chamber is improved in this case, a 5% discrepancy is introduced with the tin chamber.

To determine if the discrepancies observed with the lead and graphite wall materials discussed earlier could be explained by the presence of impurities, calculations (using a 10 cm SCD) were repeated with iron impurities in the graphite wall, and with two different alloy materials in place of the lead wall: babbitt metal with 80% lead, 15% antimony, and 5% tin; and cerrobend with 50% bismuth, 26.7% lead, 13.3% tin, and 10% cadmium. Similar to previous studies,[21,30] the iron impurity in the graphite chamber was modeled in the form of a 0.02 g/cm^2 thick ring lining the inner surface of the front wall (inner and outer radius of 1.0 and 1.1 cm, respectively). This did not account for the discrepancy with experiment since the increase in the calculated response relative to the other wall materials was only 0.5%. For the lead/bismuth alloy materials, the calculated response was 7%–8% less than that for the lead chamber, which is also not enough to account for the 15%–17% discrepancy observed.

The possibility that electron contamination in the source could account for the observed discrepancies was also investigated since the wall of the graphite chamber is not quite thick enough for full buildup (Table I). The BEAMnrc user code[29] was used to score a phase space at the position of the front face of the ion chamber due to a ^{60}Co point source (Mora spectrum[28]) filtered as described in Sec. II A 3, which was then used as an input to the CAVRZnrc calculations. Relative to the response of the aluminum chamber, the calculated response of the graphite chamber was within 1% of measurements for the chamber with side walls when electron contamination is accounted for (results shown in Fig. 6). This is a significant improvement over the above-discussed results.

III.E. Cormack and Johns chamber

Measurements and EGSnrc-calculated ionization currents for the Cormack and Johns chamber[23] with spacers are compared in Fig. 8. Results were collectively normalized to experimental values using all the results except those for lead. The RMSD is 1.5% for atomic number ranging from 6 (graphite) to 47 (silver), with a maximum discrepancy of 2.5% (silver wall, 8.6 mm cavity height). Discrepancies with

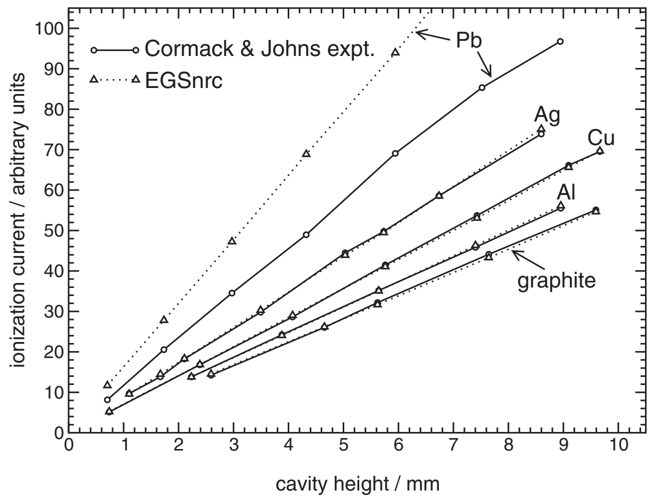

FIG. 8. Comparison of EGSnrc-calculated ionization currents as a function of cavity height with those measured by Cormack and Johns (Ref. 23) using a plane-parallel chamber. The measured values appear as originally presented, and EGSnrc results were normalized collectively to the experimental results for graphite, aluminum, copper, and silver as discussed in Sec. II B. Statistical uncertainties on the calculated results are 0.2% or less. Uncertainties on the experimental results were not reported.

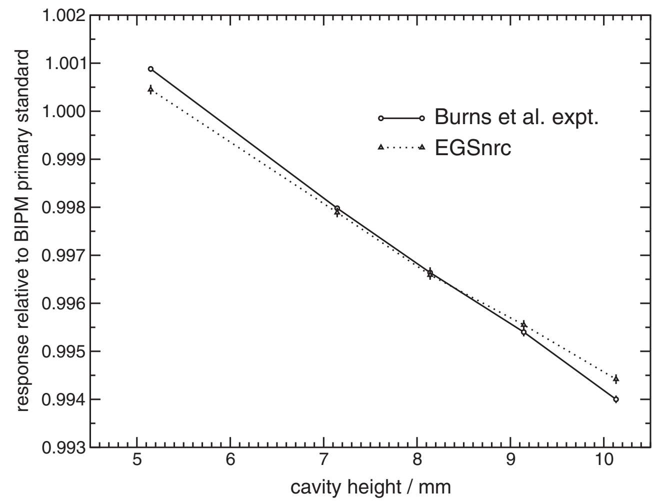

FIG. 10. Measured and EGSnrc-calculated response of the variable-volume chamber used by Burns *et al.* (Ref. 9). The reported K_{wall} and K_{an} corrections were removed from the experimental data for this comparison. The measured results are normalized to the response of the BIPM primary standard (also with K_{wall} and K_{an} corrections removed), and compared with EGSnrc calculations as discussed in Sec. II B. The uncertainty bars on the measured data, where visible, represent the statistical standard deviation of the mean of the measurements for each cavity height. The EGSnrc calculations have statistical uncertainties of 0.01%. Experimental uncertainties represent the standard deviation of repeated measurements and are within 0.015%.

the lead chamber exceed 35% and increase with increasing cavity height. The results for the chamber without spacers are shown in Fig. 9 for graphite and lead wall materials (measurements for the other wall materials were not provided). In this case, a much better agreement between calculations and measurements was obtained with the lead chamber relative to graphite (RMSD of 1.5%). Compared independently, the average RMSD was ≈1.4% for each wall material excluding the lead chamber with spacers.

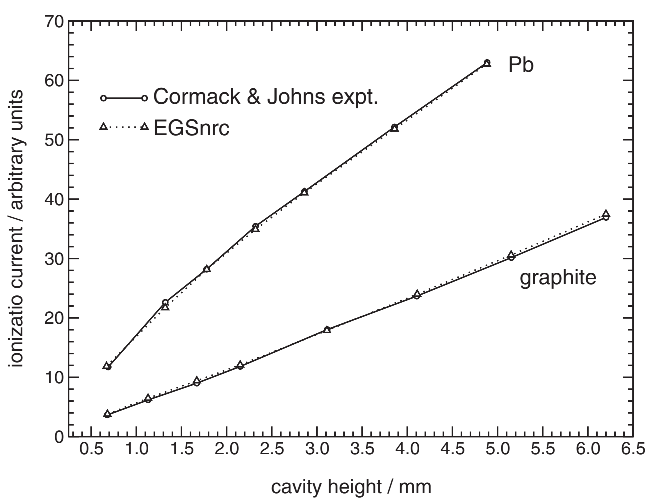

FIG. 9. As in Fig. 8 for the same chamber (graphite and lead only) without the use of spacer rings between the front and the back wall. EGSnrc results are normalized collectively to both materials. Statistical uncertainties on the calculated results are 0.2% or less. Experimental uncertainties were not reported.

III.F. Burns *et al.* chamber

The results of measurements and EGSnrc calculations of the response as a function of cavity height for the graphite chamber used by Burns *et al.*[9] are shown in Fig. 10. The fractional RMSD of the EGSnrc calculations from the measured values is 0.03%, although there is a clear, statistically significant difference in the respective trends (maximum discrepancy of 0.04%). The overall variation of the measured data is 0.7%, while only a 0.6% variation was calculated by EGSnrc. For comparison, a 0.8% variation was calculated by Burns *et al.*[9] using the PENELOPE Monte Carlo code (see Fig. 2 of their paper).

IV. DISCUSSION

IV.A. Sensitivity of comparisons to cavity volume

Although Nilsson *et al.* experimentally confirmed the bending of the mylar foils lining the inside of the chamber walls, the present authors' use of cavity height corrections with their experimental data to account for the associated decrease in cavity volume deserves further justification. In their paper, the decrease in response observed with increasing cavity height was attributed to a decrease in the relative contribution to ionization from backscattered electrons. The broad angular distribution of these low-energy electrons results in a large fraction of them directed outside the collecting volume without an equal number directed back in (recall the outer walls are outside the beam), where the fraction escaping increases with cavity height. According to this reasoning, however, the response at cavity height of 0.5 mm should be larger than at 1 mm, which is not the case in the uncorrected measurements for the chamber configured with aluminum and lead backscatter materials (Fig. 3). One can also expect a larger response at smaller cavity heights from the predictions of SA cavity theory since the SA ratio of mass-restricted stopping powers, $(\bar{L}/\rho)^{\text{air}}_{\text{med}}$, increases with decreasing cavity size when the atomic number of the wall is larger than the atomic number of the cavity gas, as demonstrated in the other experiments.[3,6] The fact that the measured data without cavity height corrections do not reflect these expectations or the results of previous experiments suggests that cavity height corrections cannot be ignored in this case. The corrections to the cavity heights used here were chosen to show that a small correction can have a big effect on the comparison with EGSnrc calculations, and does not imply that those corrections are the most appropriate.

The sensitivity to cavity volume determinations can also be demonstrated with the data of Burns *et al.* These experiments were simulated to stringently test the transport mechanics in EGSnrc, and the 0.03% agreement with this experiment confirms previous checks on the transport mechanics based on the Fano cavity test. However, in their paper, Burns *et al.*[9] discuss several experimental challenges associated with determining the response at this level of accuracy. In particular, the observed trend in the experimental data may be misrepresenting the true variation due to the effect of a physical phenomenon which is similar to a systematic offset in the cavity volume determination. One possibility is that the "effective" cavity volume is overestimated by the mechanical measurements from which it is derived due to a constant volume region in the cavity where charge is not collected.[9] The volume reduction required to bring consistency in the results is estimated to be about 10 mm^3 (0.15% of cavity volume at smallest cavity height), and taking this into account increases the variation of the experimental data shown in Fig. 10 by 10% (from 0.7% to 0.77%). As a consequence of taking this into account, the RMSD of the EGSnrc calculations would double from 0.03% to 0.06% (but with a maximum discrepancy of only 0.11%). Although this level of agreement is still comparable to the results of Fano cavity tests, it is clear that the comparison is very sensitive to the active volume of the cavity.

IV.B. Discrepancies between measurements and calculations for the Attix *et al.* and Cormack and Johns chambers

The effects of the source details and chamber composition were investigated as part of an attempt to determine the source of the few discrepancies between EGSnrc calculations and experiments by Attix *et al.*[3] and Cormack and Johns[23] (refer to Secs. III D and III E). The discrepancies between the calculated and measured responses of the Attix *et al.* chamber are surprising, particularly for the graphite chamber given the success of modeling the Whyte chamber (Fig. 5), and Cormack and Johns (Figs. 8 and 9) chamber with this material relative to other materials. When modeling the source as a pure photon beam, this discrepancy could not be accounted for by the details of the incident photon spectrum, the source-to-chamber distance, or impurities. This discrepancy could also not be explained by calculated values of $K^{\text{expt}}_{\text{wall}}$ used to reverse correct the data for graphite and aluminum in the Attix case. $K^{\text{expt}}_{\text{wall}}$ values for graphite and aluminum were very similar (Table II), and so the relative differences between the graphite and aluminum experimental data sets (Figs. 6 and 7) are nearly identical to how they were originally presented.[3] Ignoring additional corrections, the response of the graphite and aluminum chambers should be proportional to $(\bar{L}/\rho)^{\text{air}}_{\text{graphite}}(\bar{\mu}_{\text{en}}/\rho)^{\text{graphite}}_{\text{air}}$ and $(\bar{L}/\rho)^{\text{air}}_{\text{Al}}(\bar{\mu}_{\text{en}}/\rho)^{\text{Al}}_{\text{air}}$, respectively, in which case the response of the aluminum chamber should be roughly 10% higher than the graphite chamber.[16,39] This is the case for the EGSnrc calculations of these chambers, and for measurements and calculations of the other chambers investigated here. It is even confirmed by the analytical calculations included by Attix *et al.* in their paper.[3] When a source contaminated with electrons is used, the discrepancies with the graphite chamber are removed. Thus, the measured over response of the graphite chamber is due to the fact that the graphite walls do not provide full buildup, which allows high-energy electrons originated from the filter to penetrate the front wall and increase the response. Unfortunately, details about the source collimation and filter position were not reported by Attix *et al.*,[3] which prevents a more thorough investigation of this effect.

In addition to the above-mentioned problems with the absolute comparisons, it is interesting to note that the best results are obtained at low SCDs. A small SCD is consistent with the activity of the source (1 Ci), the amount of filtration ($\approx$16 g/cm^2), and their stated aim of producing pA currents. Similar experiments by Burlin[4] performed shortly after Attix *et al.* also used a small SCD (8.25 ± 0.02 cm) for a 250 mCi ^{60}Co source without filtration.

For the Cormack and Johns chamber with lead walls, calculations significantly overestimated the corresponding experimental values (Fig. 8). This discrepancy is comparable to the one observed with calculations of the Attix *et al.* chamber[3] with lead walls but it only applies to the lead chamber with spacers. Rather than attributing the above-mentioned discrepancies to an experimental fault, one could argue that there exists a shortcoming of the EGSnrc model of the lead chamber, such as inadequate modeling of the physics, or a problem with the cross sections for lead. However, this is inconsistent with the excellent agreement obtained in the simulation of this chamber without spacers (Fig. 9), or with similar agreement seen with the Nilsson *et al.* chamber (Figs. 3 and 4) and with previous reports.[15] Based on these results the present authors can only speculate that the values published by Cormack and Johns for the lead chamber with spacers represent data for another combination of materials.

V. CONCLUSIONS

In this investigation, the EGSnrc Monte Carlo code was evaluated for its ability to calculate ion chamber response to ^{60}Co using experimental data as benchmarks. With the exception of the Attix *et al.* results for two wall materials and one set of results for Cormack and Johns, the RMSD of EGSnrc calculations of chamber response in a ^{60}Co beam as a function of cavity height or cavity air pressure are generally within 1.5% when compared collectively for a variety of chamber wall materials and cavity dimensions/air pressures which, themselves, show variations of up to 300%. The level of agreement one can expect in these comparisons depends on the accuracy of both the underlying cross sections used and on the uncertainty on the experimental measurements, which was assumed to be $\approx$1% for the older experiments. These comparisons are therefore consistent with expectations. When the results for each wall material are considered independently, the comparisons are much less dependent on the uncertainties in the cross sections and the RMSD of EGSnrc calculations range between 0.03% and 1.4%. This is comparable to the estimated uncertainty on the experiments, except for those of Burns *et al.*[9] Simulations of the latter high-precision experiments were within 0.03%–0.06% depending on the cavity volume assumed in the measurements, which experimentally confirms the accuracy of the transport mechanics used by EGSnrc at these energies established in previous theoretical investigations. Based on the agreement observed here, NIST XCOM photon cross sections can be used with the EGSnrc Monte Carlo code to reliably calculate the variation in chamber response with changes in cavity dimension and wall material at ^{60}Co energies with an accuracy of $\approx$1.5%. Future attempts to test EGSnrc and its cross sections at a higher level of precision will require a more accurate knowledge of chamber response measurements as a function of wall material and cavity dimension, including accurate knowledge of the active cavity volume, composition and dimensions of the chamber components, and details of the source.

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