The replacement correction factor for the BIPM flat cavity ion chamber and the value of *W/e*

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A graphite flat cavity ionization chamber is used at the BIPM in France to determine the absorbed dose to graphite in a ^{60}Co photon beam and thereby used to determine the product of the value of W/e, the average energy required to produce an ion pair in dry air, and the value of $(\bar{L}_\Delta/\rho)_a^C$, the mean restricted mass collision stopping-power ratio for graphite to air in a ^{60}Co beam. The accuracy of the (W/e) $(\bar{L}_\Delta/\rho)_a^C$ value thus determined depends upon the accuracy of the perturbation correction factors adopted for this chamber. The perturbation effect of this chamber was accounted for by the replacement correction factor whose value was calculated by an analytical method and confirmed by an EGS4 Monte Carlo calculation. The purpose of this study is to investigate the validity of the analytical and the EGS4 calculations by using recently established methods and the EGSnrc Monte Carlo code, a much improved version of EGS4, to calculate the replacement correction factors for the graphite chamber. It is found that the replacement correction factors used for the BIPM chamber are not correct: the values used are smaller than they should be by about 1%. This leads to a 1% overestimation of the (W/e) $(\bar{L}_\Delta/\rho)_a^C$ value determined by using this chamber. This implies that ^{60}Co air kerma standards that are directly proportional to this product need to be reduced by 1%. Based on the values of the replacement correction factors calculated in this study, and on the value of $(\bar{L}_\Delta/\rho)_a^C$ evaluated from ICRU Report No. 37 stopping power for graphite, the value of W/e determined by using the BIPM chamber should be 33.61 ± 0.08 J/C. If a more recent value of mean excitation energy for graphite (86.8 eV) and grain density are used to evaluate the graphite stopping power, then the value obtained for W/e is 34.15 ± 0.08 J/C. © *2008 American Association of Physicists in Medicine*. [DOI: 10.1118/1.2975148]

Key words: replacement correction factor, stopping power, W/e, EGSnrc, graphite calorimeter, ion chamber, primary standards, air kerma, absorbed dose

I. INTRODUCTION

At the Bureau International des Poids et Mesures (BIPM) in France, a graphite flat cavity ionization chamber is used to determine the absorbed dose to graphite in a ^{60}Co beam. This chamber (hereafter referred to as the BIPM chamber) is similar to a normal plane-parallel chamber except there is a circular collecting electrode made of graphite at the center of the cavity. The BIPM chamber played a central role in the determination of the value of the product of W/e, the energy deposited by electrons slowing down in dry air per unit charge released, and $(\bar{L}_\Delta/\rho)_a^C$ (or in IAEA's notation $s_{C,a}$), the mean restricted mass collision stopping-power ratio for graphite to air in a ^{60}Co beam. The value of W/e is of fundamental importance to the study of ionizing radiations and radiation dosimetry. Many experiments[1,2] have been performed in the past to determine W/e. For low-energy electrons (up to 7 keV), W/e can be measured directly.[2] For high-energy photon beams, e.g., ^{60}Co and linac beams, direct measurement of W/e becomes impossible as the range of electrons is too large. Instead, cavity theory has to be employed in determining W/e, and in fact, often only the product (W/e) $(\bar{L}_\Delta/\rho)_a^C$ is directly measured. The value of W/e can then be derived if one knows the value of $(\bar{L}_\Delta/\rho)_a^C$. Two important experiments measuring the product (W/e) $(\bar{L}_\Delta/\rho)_a^C$ were performed by Niatel *et al.*,[3] and the W/e value obtained from the measurements carries a significant weight in determining the standard value of 33.97 ± 0.05 J/C recommended by Boutillon and Perroche-Roux[1] and adopted by convention by all primary standard labs. Niatel *et al.* used two independent ways[3] to determine (W/e) $(\bar{L}_\Delta/\rho)_a^C$. In the first method, they compared the ionometric readings from the BIPM chamber to the calorimetric standards from four national laboratories for the absorbed dose in graphite irradiated by a ^{60}Co beam. The W/e value thus determined is 33.96 ± 0.08 J/C when using ICRU Report No. 37[4] stopping powers to evaluate $(\bar{L}_\Delta/\rho)_a^C$. This value was later revised to 33.99 ± 0.08 J/C by Boutillon,[5] after taking into account the radial nonuniformity effect[6] for the ^{60}Co beam and the gap correction[7] for the calorimeters (both of which were ignored in the original four comparisons), and also after considering the measurements with three more absorbed dose calorimeters.

In the second method, they measured the exposure rate for a ^{60}Co source of known activity and compared this to the calculated exposure rate to obtain a value of $33.81 \pm 0.42\%$ J/C for W/e. Again, ICRU Report No. 37

stopping powers were used to evaluate $(\bar{L}_\Delta/\rho)_a^C$. As the electron stopping power in a medium depends on the mean excitation energy (or I value) of the medium, so does the stopping-power ratio $(\bar{L}_\Delta/\rho)_a^C$ and hence the value of W/e. Currently ICRU Report No. 37 uses an I value of 78 ± 7 eV (2σ) for graphite.[4] A newer experiment[8] has given an I value of 86.8 ± 1.2 eV for graphite with a much reduced uncertainty. If this new I value is used in evaluating the stopping power, the stopping-power ratio $(\bar{L}_\Delta/\rho)_a^C$ in a ^{60}Co beam would be decreased by 1.6%. Consequently, the above-obtained value of W/e should be increased by the same amount. However, this is an extreme case since the original ICRU value was based on four previous experiments, several with much smaller uncertainties than the evaluated value of 78 ± 7 eV. Taking a weighted average of all five experiments gives $I=84.5 \pm 5$ eV (2σ), although we will continue to use the two extreme cases in this work.

In order to use the BIPM chamber to determine accurately the absorbed dose to graphite in a ^{60}Co beam, among other things, the perturbation effect caused by the chamber must be reliably determined. Since the chamber is used in a graphite phantom, the only perturbation correction factor related to this chamber is the replacement correction factor, P_{repl}, or K_p as denoted by Niatel *et al.*[3] in their determination of the value of (W/e) $(\bar{L}_\Delta/\rho)_a^C$. As the P_{repl} value for the BIPM chamber is directly related to the determination of W/e, accurate knowledge of the value becomes very important. Boutillon[9] used an analytical approach to calculate the value of P_{repl} for the BIPM chamber at different depths in a graphite phantom irradiated by a ^{60}Co beam. For situations in which either the front face or the center of the cavity was taken as the point of measurement (POM), the values of P_{repl} were found to be 1.007 and 0.989, respectively, at a depth of 5 g/cm^2. Ferreira *et al.*[10] used the EGS4 Monte Carlo code to calculate the P_{repl} value for the same chamber and got the same results as Boutillon. Niatel's experimental results[11] were consistent with Boutillon's calculations, although only the ratio of P_{repl} values as a function of depth for the two POMs was verified. However, Boutillon stated that the P_{repl} values for the BIPM chamber were calculated "by applying the same type of analysis as that used for the determination of exposure,"[9] by which she meant as used for the calculation of the correction for axial nonuniformity needed for the exposure standard. It was pointed out in the early 1990s that this method was incorrect[12] and, in a recent paper, Burns[13] showed that this particular correction factor was incorrect by 0.63%, and the new value is used in the BIPM primary standard for air kerma (exposure).[14] This suggests that a reevaluation of the P_{repl} values for the BIPM chamber is appropriate. Ferreira *et al.*[10] also calculated the perturbation corrections for the cylindrical thimble-type standard graphite ion chamber of the Instituto de Radioproteçao e Dosimetria (IRD, Brazil) in a graphite phantom irradiated by a ^{60}Co beam. The results were consistent with the experimental values of de Almeida *et al.*,[15] who measured the readings from both the IRD chamber and the BIPM chamber in the same beam thereby giving the ratio of P_{repl} for the two chambers. Thus the measured P_{repl} values for the IRD chamber depend upon the P_{repl} values for the BIPM chamber.

In a recent study,[16] systematic and reliable ways of calculating P_{repl} in photon beams by Monte Carlo methods have been established. One of the conclusions from that study is that, for plane-parallel chambers in photon beams, P_{repl} is unity if the midplane of the chamber cavity is taken as the point of measurement. This seems to contradict the above-given P_{repl} value (0.989) for the BIPM chamber when the center of the cavity is taken as the point of measurement. Additionally, the limitations of the EGS4 code with the PRESTA[17] algorithm in calculating ion chamber responses in a ^{60}Co beam were pointed out years ago[18] when it was shown that there is about a 1% systematic error in the calculation results for a graphite ion chamber. In this study, the EGSnrc[19] Monte Carlo code is used, with the techniques described earlier,[16] to calculate the P_{repl} values for both the BIPM chamber and the IRD chamber in a graphite phantom irradiated by a ^{60}Co beam. The EGSnrc Monte Carlo code system uses new electron transport and boundary crossing algorithms[19] compared to the old EGS4/PRESTA version; thus the calculation accuracy of ion chamber response is dramatically improved.[20,21] The values of W/e obtained by Niatel *et al.*[3] and later revised by Boutillon[5] are reevaluated with the new perturbation correction factors calculated in this work.

II. CALCULATION METHODS

II.A. Default EGSnrc calculation

The EGSnrc user-codes CAVRZnrc[22] and CAVITY[23] are used to model the BIPM chamber and the IRD chamber, respectively. The chamber and the radiation source geometries are the same as those described by Ferreira *et al.*[10] and Boutillon.[9] The spectrum for the ^{60}Co beam is taken from Mora *et al.*[24] A monoenergetic photon beam of energy 1.25 MeV was also used in the calculation to study the sensitivity of the calculated P_{repl} values to the radiation spectrum. The graphite phantom and the BIPM chamber wall have a density of 1.80 g/cm^3, which is used in the calculation. The IRD chamber wall has a density of 1.70 g/cm^3. Since the density of graphite varies, a graphite phantom of density 1.70 g/cm^3 is also used in the calculations to study if there is any dependence on the phantom density. The electron stopping-power density correction for the bulk graphite density (1.70 g/cm^3) is used in most of the calculations with standard ICRU Report No. 37 stopping powers. The density effect correction for the grain (or crystallite) density (2.26 g/cm^3) together with a graphite stopping power calculated from the extreme I value of 86.8 eV is also used in the calculation for a sensitivity test. The boundary crossing and electron transport algorithm are EXACT and PRESTA-II, respectively. Electron energy thresholds (AE) and cut-offs (ECUT) of both 10 and 1 keV (kinetic energy) are used (i.e., either AE=ECUT=10 keV or AE=ECUT=1 keV), and the same values are used for the corresponding photon thresholds (AP and PCUT). The graphite/air stopping-power ratio

TABLE I. Comparison of P_{repl} values calculated by different methods for the BIPM chamber at depth of 4 g/cm^2 in a graphite phantom when the front face of the cavity is taken as the point of measurement. The calculation is done by the EGSnrc user-code CAVRZnrc. Three methods, SPR, HDA, and LDW (see the text for brief descriptions, or Ref. 16 for details), are used with different particle energy thresholds and cut-offs. ECUT (PCUT) is the same as AE (AP) in all cases. AE is expressed as kinetic energy.

	SPR (Δ=14 keV)	HDA	LDW
AE=1 keV AP=1 keV	1.0171 ± 0.0012	1.0176 ± 0.0013	1.0176 ± 0.0012
AE=10 keV AP=10 keV	1.0165 ± 0.0009	1.0174 ± 0.0008	1.0181 ± 0.0008

is calculated by SPRRZnrc[22] with a cut-off energy of 14 keV for the BIPM chamber. This cut-off energy is the minimum energy needed on average for an electron to cross the cavity as determined by Niatel *et al.*[3] Different methods labeled SPR, HDA (high-density air), and LDW (low-density water), as described previously,[16] are used in the calculation of P_{repl}. The SPR method is the typical way of calculating P_{repl} by using the Spencer–Attix relation, i.e., the value of P_{repl} is calculated as the quotient of the phantom-to-cavity dose ratio and the mean restricted stopping-power ratio of the two media (phantom and cavity). The phantom-to-cavity dose ratio is the ratio of dose in phantom at the reference point, in the absence of the cavity, to the dose in the collecting volume of the cavity, when the cavity is present at the reference point. The HDA and LDW methods are two direct methods of calculating P_{repl} without the need of the stopping-power ratio calculation and attendant uncertainty in selecting the cut-off energy Δ. For the HDA method, the dose in phantom is calculated as the dose in a thin slab centered at the reference point, with the slab being replaced by high-density air which has all the characteristics of air except its density is equal to that of the phantom. For the LDW method, the air in the cavity is replaced by a low-density phantom material which has all the characteristics of the phantom except its density being the same as that of air. For both the direct methods, the phantom-to-cavity dose ratio will give P_{repl} directly since the stopping-power ratio vanishes as the materials are the same. In this study, a low-density graphite material (1.2048×10^{-3} g/cm^3) and a high-density air material (1.80 g/cm^3) are created in order to use the LDW and the HDA methods.

Tables I and II list P_{repl} values for the BIPM chamber calculated by different methods and for different scenarios in

TABLE II. Comparison of P_{repl} values calculated for different scenarios for the same geometry as described in Table I. Electron and photon cut-offs are AE=10 keV (kinetic energy) and AP=10 keV. The LDW method (see the text) is used in the calculation.

	1.80 g/cm^3 phantom, Spectrum source	1.70 g/cm^3 phantom, spectrum source	1.80 g/cm^3 phantom, 1.25 MeV photon
P_{repl}	1.0181 ± 0.0008	1.0169 ± 0.0012	1.0148 ± 0.0012

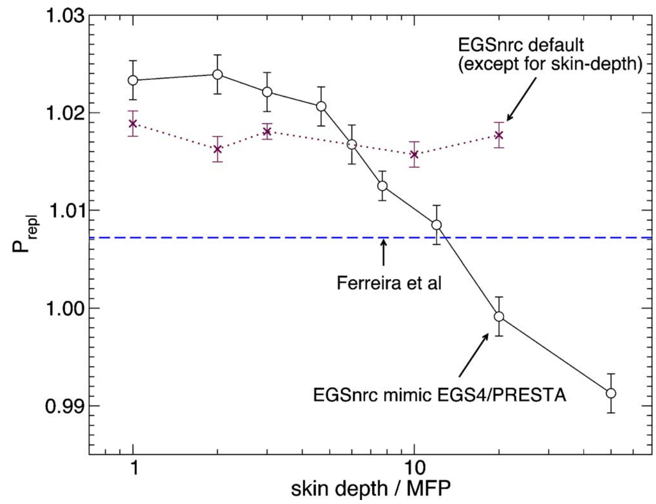

FIG. 1. Calculated P_{repl} for the BIPM chamber by the default EGSnrc calculation and by using EGSnrc to mimic the EGS4/PRESTA algorithm. The user code is CAVRZnrc. P_{repl} is calculated by the SPR method (see the text) and is shown as a function of the skin depth for boundary crossing in units of mean free paths (MFP) between two successive electron interactions. The horizontal dashed line indicates the EGS4 calculation by Ferreira *et al.*, (Ref. 10), with an unknown skin-depth parameter. The default EGS4 skin depth is indicated by an arrow to the dashed line. The calculation is done at a depth of 4 g/cm^2 in a graphite phantom when the front face of the cavity is taken as the point of measurement.

order to assess the sensitivity of the calculated values to these parameters. All methods give the same result within calculation statistical uncertainties (~0.1%), except for the monoenergetic photon beam. In this extreme case the value is about 0.3% lower, though barely of statistical significance. It is assumed therefore that the difference between the Mora spectrum and the BIPM spectrum has a negligible effect on the calculated P_{repl} values. These results demonstrate that using 10 keV as the energy cut-off is sufficient for this chamber, in support of the previous study for other chambers.[16] However, as discussed in the following, the results are significantly different (about 1%) from the Ferreira *et al.*[10] values calculated using EGS4/PRESTA.

II.B. EGS4 calculation mimicked by EGSnrc code

In order to investigate the cause of this discrepancy with the EGS4 results, the CAVRZnrc code was used to mimic the old EGS4/PRESTA calculations.[19] In doing so, the boundary crossing and electron transport algorithm are both set to PRESTA-I. The maximum step size (SMAX) is 5 cm. The maximum energy loss per step (ESTEPE) is 0.04, corresponding to the value used by Ferreira *et al.*[10] Electron and photon energy thresholds/cut-offs are 512 keV (or 1 keV in kinetic energy) and 1 keV, respectively. The skin depth for boundary crossing, which was not reported by Ferreira *et al.*,[10] is set to a variety of values to check the dependence of the calculated chamber response. Figure 1 shows the values of P_{repl} for this EGS4-mimic calculation as a function of the value of the skin-depth parameter. The variation of the calculated P_{repl} values can be as large as 3%; and it covers both the result by Ferreira *et al.* and the result in this work by

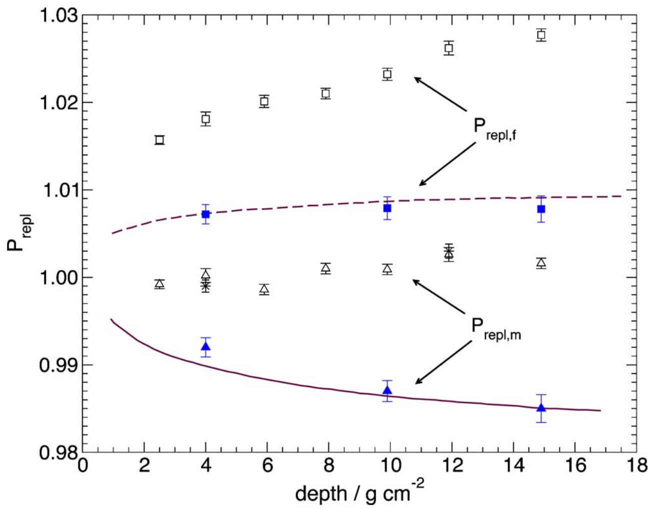

FIG. 2. Calculated P_{repl} values (open symbols) for the BIPM chamber at various depths in a graphite phantom with either the front face ($P_{repl,f}$) or the midplane ($P_{repl,m}$) of the cavity taken as the point of measurement. The calculation is done by the LDW method (see the text) with AE=10 keV (kinetic energy) and AP=10 keV. The values from Boutillon (Ref. 9) and from Ferreira *et al.* (Ref. 10) are shown as lines and closed symbols, respectively. The stars represent the $P_{repl,m}$ values calculated using stopping powers evaluated using the grain density (2.26 g/cm^3) to calculate the density effect correction and an I value of 86.8 eV.

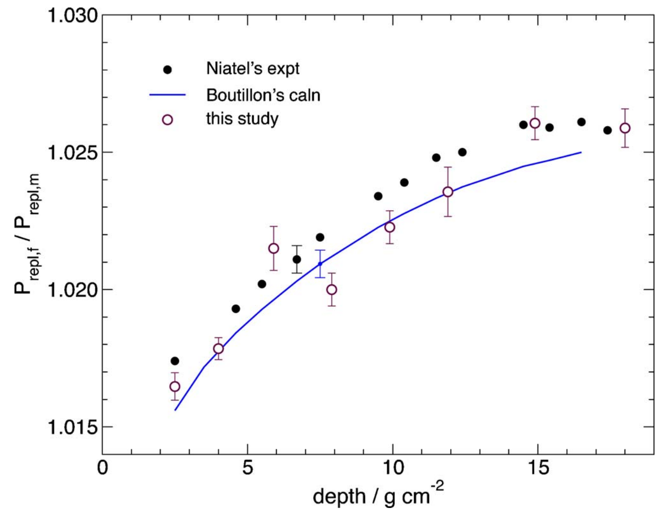

FIG. 3. Calculated ratio $P_{repl,f}/P_{repl,m}$ (open circles) for the BIPM chamber at various depths compared with the experimental values (closed circles) and the analytical calculation by Boutillon (solid line). Both the measurement and the analytical calculation have an uncertainty of about 0.05% (1σ)—Ref. 11.

the default EGSnrc calculation. The default EGS4 skin depth is about 7.7. At this point, P_{repl} is about 1.012, half a percent higher than the value given by Ferreira *et al.* This difference is probably because the EGS4-mimic calculation is not a true EGS4 calculation and there are still other variable parameters. The results in Fig. 1 demonstrate that EGS4/PRESTA is not reliable in calculating ion chamber responses. In EGSnrc, the calculation of ion chamber response is essentially independent of either skin depth or ESTEPE.[21]

III. RESULTS AND DISCUSSIONS

III.A. P_{repl} for BIPM chamber

Figure 2 compares P_{repl} values for the BIPM chamber calculated in this study to those calculated by Boutillon[9] and by Ferreira *et al.*[10] at various depths in a graphite phantom irradiated by a 100 cm^2 ^{60}Co beam. The values of P_{repl} are obtained for two cases: $P_{repl,f}$ for the front face as the POM, and $P_{repl,m}$ for the midplane as the POM. In both cases the calculated P_{repl} values in this study are about 1% larger than the corresponding values by Boutillon and Ferreira *et al.*, irrespective of the depth. The other distinction is that the $P_{repl,f}$ values in this study increase slightly with depth, while $P_{repl,m}$ values remain close to unity, in contrast to the results of Boutillon and of Ferreira *et al.* in which $P_{repl,f}$ does not depend much upon the depth but $P_{repl,m}$ decreases slightly with depth. Note that the results here for $P_{repl,m}$ are consistent with our previous study[16] for another plane-parallel chamber (NACP02) in a ^{60}Co beam, where it was found that the POM should be at the center of the cavity instead of the front face in order to have $P_{repl}=1$.

To investigate the sensitivity of the calculated P_{repl} values to the stopping powers used, the values of $P_{repl,m}$ are also calculated for a graphite phantom of density 1.80 g/cm^3 but with the graphite stopping power calculated using the density effect correction evaluated for the grain density of graphite (2.26 g/cm^3) together with the I value of 86.8 eV. Figure 2 shows that the values of $P_{repl,m}$ for this calculation (star symbols) is the same as $P_{repl,m}$ for the normal graphite phantom which uses the density effect correction evaluated for the bulk density (1.70 g/cm^3) and the standard ICRU Report No. 37 stopping powers. These results demonstrate that the $P_{repl,m}$ value is not sensitive to the density correction or the I value used.

Although there is about a 1% difference in the values of P_{repl} calculated in this work compared to the old values for the two POMs, the ratio of the two factors, $P_{repl,f}/P_{repl,m}$, is almost the same as before, as shown in Fig. 3. The measurement made by Niatel[11] was considered to be experimental support of Boutillon's[9] calculations. However, as mentioned in Sec. I, the experiment measured only the ratio of $P_{repl,f}$ to $P_{repl,m}$. In this sense, the P_{repl} values calculated in this work are also supported by the experiment.

III.B. P_{repl} for IRD chamber

There are no analytically calculated P_{repl} values for the IRD chamber. Ferreira *et al.*[10] calculated P_{repl} values of the IRD chamber by the EGS4 Monte Carlo code and found the results agreed with the experimental values of de Almeida *et al.*[15] However, as shown in Table III, the P_{repl} values calculated for the IRD chamber in the present study differ from those from the measurements by about 1%. de Almeida *et al.*[15] deduced the P_{repl} values for the IRD chamber by comparing readings from the IRD chamber to those from the BIPM chamber. Thus the measured P_{repl} values for the IRD chamber are directly proportional to the P_{repl} values of the

TABLE III. Comparison of P_{repl} values at various depths for the IRD chamber. The measurements, which depend directly on the P_{repl} values of the BIPM chamber, were done by de Almeida *et al.* (Ref. 15).

Depth (g/cm^2)	Experimental values	This study
4.0	0.9726 ± 0.0013	0.982 ± 0.001
5.0	0.9696 ± 0.0014	0.982 ± 0.001
9.9	0.9670 ± 0.0018	0.980 ± 0.001
14.9	0.9640 ± 0.0018	0.979 ± 0.001

BIPM chamber, i.e., they are not independent: If P_{repl} values of the BIPM chamber are wrong by 1%, then so are those of the IRD chamber. In reality, the experiment measured only the ratio of the P_{repl} values for the two chambers, $P_{repl,IRD}/P_{repl,BIPM}$, where $P_{repl,IRD}$ is the value for the IRD chamber and $P_{repl,BIPM}$ is the value for the BIPM chamber when the midplane is taken as the POM. Figure 4 shows the measured ratios of the P_{repl} values for the two chambers. The open circles represent the same ratios calculated in this study. The agreement is well within experimental uncertainties, and thus the P_{repl} calculation in this study for the IRD chamber is also supported by the measurements.

III.C. Values of $(W/e)\ (\bar{L}_\Delta/\rho)_a^C$ and W/e

The first method Niatel *et al.*[3] used to determine the value of $(W/e)\ (\bar{L}_\Delta/\rho)_a^C$ was to compare the measured absorbed dose to graphite at various depths irradiated in a ^{60}Co beam by the BIPM chamber to that measured from the calorimetric standards of four national standards laboratories. Note that the value of $(W/e)\ (\bar{L}_\Delta/\rho)_a^C$ is inversely proportional to the perturbation correction factor, P_{repl}, of the BIPM chamber [see Eq. (2) in their paper—Ref. 3]. This means that the measured product $(W/e)\ (\bar{L}_\Delta/\rho)_a^C$ depends upon the accuracy of the P_{repl} values used for the BIPM chamber. As stated

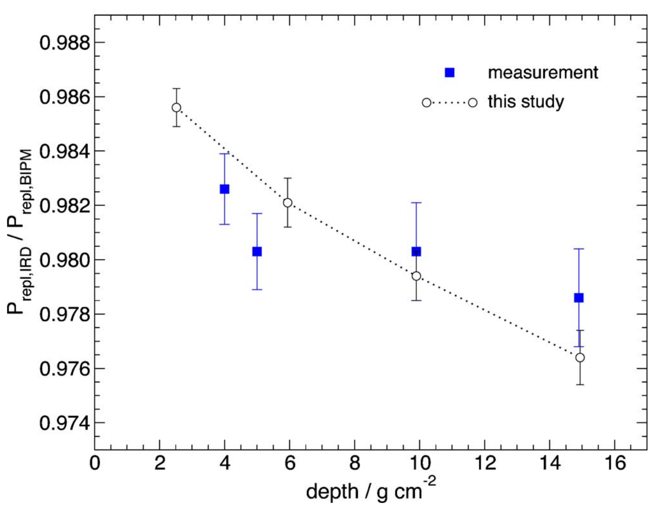

FIG. 4. Comparison at various depths of the ratios of P_{repl} values of the IRD chamber to those of the BIPM chamber (with the point of measurement at midplane) as measured by de Almeida *et al.*—Ref. 15 (squares), to the same ratio calculated in this study (circles).

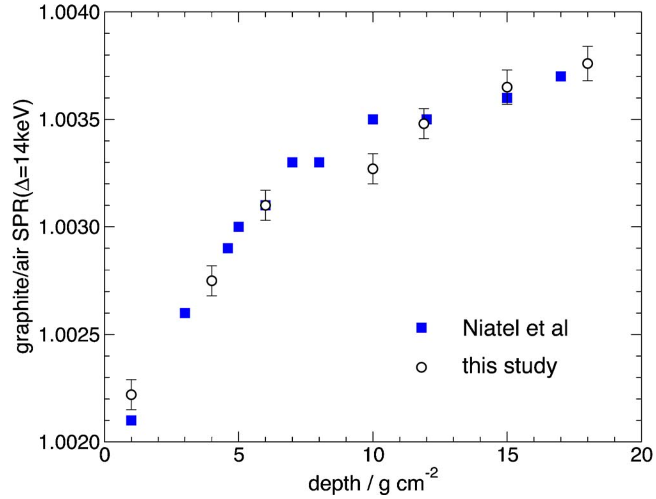

FIG. 5. The graphite/air mean restricted stopping-power ratio for use with the BIPM chamber as a function of depth in a graphite phantom. Squares are the values calculated by Niatel *et al.* (Ref. 3). Circles are the values calculated by SPRRZnrc in this study. The energy threshold for the stopping-power ratio calculation is $\Delta = 14$ keV.

earlier, there is about a 1% difference between the P_{repl} values used previously for the BIPM chamber and those calculated in this study. Although the values of P_{repl} for the BIPM chamber have been revised by Boutillon,[5] the change is not more than 0.07% and thus is totally insignificant. Hence our new values would lead to a different value of the measured product $(W/e)\ (\bar{L}_\Delta/\rho)_a^C$ determined using the BIPM chamber. As shown earlier, the values of P_{repl} in this study for the BIPM chamber, when the midplane is taken as the POM, are very close to unity at different depths (see Fig. 2), so it is a good approximation to assume it is 1.000. Thus the quantity $(W/e)\ (\bar{L}_\Delta/\rho)_a^C$ associated with the new P_{repl} values from this study can be obtained by multiplying the old $(W/e)\ (\bar{L}_\Delta/\rho)_a^C$ value at each depth by the correction factor P_{repl} calculated by Boutillon[5] at that depth. The value of W/e can be obtained by dividing the measured product $(W/e)\ (\bar{L}_\Delta/\rho)_a^C$ by $(\bar{L}_\Delta/\rho)_a^C$. Niatel *et al.* evaluated the values of $(\bar{L}_\Delta/\rho)_a^C$ as a function of depth in the graphite phantom. They used stopping powers from ICRU Report No. 37 (Ref. 4) with an energy threshold $\Delta = 14$ keV. Their results are shown in Fig. 5 along with our values for the same quantity. There is excellent agreement between the values calculated by Niatel *et al.* and the values calculated by SPRRZnrc in this work. Figure 6 shows the revised values of W/e by Boutillon[5] for the original four comparisons (30 points) by Niatel *et al.*,[3] taking into account the adjustments of the gap correction, the radial nonuniformity correction, and P_{repl}. The stopping-power ratio in Fig. 5 has been used to evaluate $(\bar{L}_\Delta/\rho)_a^C$ in order to obtain W/e. The average value of W/e from Boutillon's revision (dashed line) of the original four comparisons is 34.01 J/C, very close to the value of 33.99 J/C (Ref. 5) obtained when the additional three comparisons were taken into account. Figure 6 also presents the values of W/e determined in this study based on Boutillon's

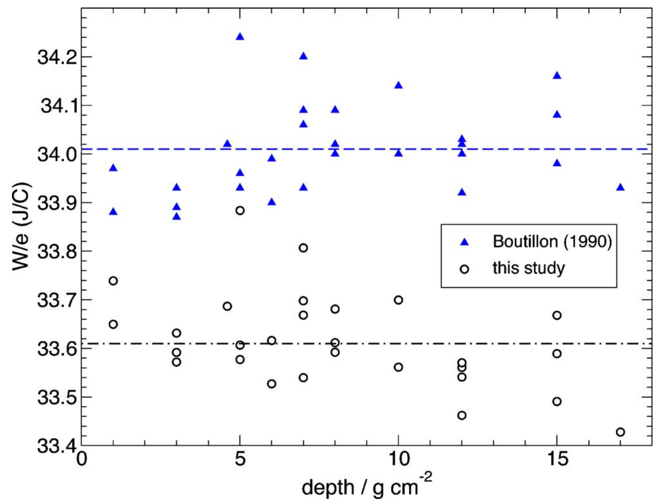

FIG. 6. Values of W/e obtained from absorbed dose comparisons between the BIPM chamber measurement and the calorimetric measurements of four national standards. The experiments actually measured (W/e) $(\bar{L}_\Delta/\rho)_a^C$ and the W/e values are obtained by dividing (W/e) $(\bar{L}_\Delta/\rho)_a^C$ by the values of $(\bar{L}_\Delta/\rho)_a^C$, which are evaluated based on ICRU Report No. 37 stopping powers. Triangles are the values revised by Boutillon (Ref. 5) for the original values obtained by Niatel *et al.* (Ref. 3) for the four comparisons. Circles are the values obtained by assuming unity for the values of $P_{\rm repl}$ for the BIPM chamber.

revision of the original data but assuming $P_{\rm repl}=1$. The dotted-dash line illustrates the average value, 33.61 J/C, for the new determination in this work. The new W/e value in this study is about 1.2% lower than that determined by applying Boutillon's corrections to the earlier results by Niatel *et al.* [actually, it is the new (W/e) $(\bar{L}_\Delta/\rho)_a^C$ value that is lower than the earlier one]. Figure 6 also shows a small variation with depth in the graphite phantom for the W/e values determined by Boutillon. But the trend is diminished when the $P_{\rm repl}$ values in this work are applied. This is consistent with the general belief that the W/e value should not change with depth. In this study, the statistical uncertainties of the calculated $P_{\rm repl}$ values for the BIPM chamber are around 0.05%–0.08%, which is about the same as the uncertainty (0.06%) used by Niatel *et al.*[3] for their $P_{\rm repl}$ values used to determine the value of W/e. So the overall uncertainty of the value of W/e in this study remains about the same as the earlier one, i.e., 0.23% (1σ).

As mentioned in Sec. I, the W/e value obtained by Niatel *et al.*[3] with their second method was $33.81\pm0.42\%$ J/C. This value is inversely proportional to the BIPM's ^{60}Co exposure standard (or air kerma standard) which has recently been increased by 0.54%.[14] That means the W/e value determined by the second method of Niatel *et al.* should be decreased by 0.54% to a value of $33.63\pm0.42\%$ J/C, which is basically the same as our value of $33.61\pm0.23\%$ J/C for the calorimetry-based method.

The W/e value determined in Fig. 6 depends on the selection of $(\bar{L}_\Delta/\rho)_a^C$ value, which in turn depends on the mean excitation energy (I value) of graphite. If an I value of 86.8 eV and density effect correction based on the grain density are used to evaluate the graphite stopping power, a calculation by SPRRZnrc for the values of $(\bar{L}_\Delta/\rho)_a^C$ at various depths in a graphite phantom in a ^{60}Co beam gives values of $(\bar{L}_\Delta/\rho)_a^C$ which are 1.6% lower at all depths, than those shown in Fig. 5. On the other hand, the value of $P_{\rm repl}$ remains unchanged as shown in Fig. 2. Therefore, in this situation, the W/e value would increase by 1.6%, from 33.61 to 34.15 J/C.

Büermann *et al.*[25] recently did experiments comparing the ionometric and calorimetric determination of absorbed dose to water in a ^{60}Co beam. The ionometric absorbed dose is directly proportional to the (W/e) $(\bar{L}_\Delta/\rho)_a^C$ value. They found that the absorbed dose obtained from the ionometric method, with the standard W/e value of 33.97 J/C and the value of $(\bar{L}_\Delta/\rho)_a^C$ from ICRU Report No. 37,[4] is about 1.4% higher (with relative uncertainty of 0.36%) than that measured with the water calorimeter. Thus if the proposed 1.2% lower value of W/e is used, their measurements become consistent at the 0.2% level. In their study they also did an analysis in which they used stopping powers based on a graphite I value of 86.8 eV instead of 78 eV used in ICRU Report No. 37. This reduces the value of $(\bar{L}_\Delta/\rho)_a^C$ in a ^{60}Co beam by roughly 1.5%.[26] But this change in stopping-power ratio also implies a change in W/e value as described earlier. If one takes into account both the change in the stopping-power ratio and the change in the measured product of (W/e) $(\bar{L}_\Delta/\rho)_a^C$ then their analysis of their measured data is still consistent. Thus their measurements do not present any information on the preferred value of the I value for graphite since, in essence, their experiment was sensitive to the product of (W/e) $(\bar{L}_\Delta/\rho)_a^C$ rather than either component separately. In fact their experiment could be considered a measurement of this product.

A direct measurement of the W/e value[2] for low-energy electrons has shown that the W/e value approaches a constant value very close to 34 J/C, for electron energy above about 4 keV. As the value of W/e is generally believed to remain constant for higher energies, referring to the above-presented discussions, this suggests that a higher I value (e.g. 86.8 eV, or the mean value of 84.5 ± 5 eV mentioned in Sec. I) may be more appropriate than that used in ICRU Report No. 37. A higher I value for graphite is also indicated by an experiment[27] comparing the air kerma rate measured with a free air chamber to that with a cavity ion chamber. However, this experiment is also subject to uncertainties due to what density effect to use and the possibility of significant fluence perturbation factors at the low photon energies involved.

IV. CONCLUSIONS

Using the EGSnrc Monte Carlo code system, together with the recently established methods of calculating the replacement correction factors for ion chambers, it is found that the replacement correction factors used in the past for the BIPM graphite flat cavity ion chamber are not correct. The values used previously are smaller than they should be by about 1%. As this chamber was used to determine the value of W/e, this 1% discrepancy in the perturbation factor leads to a 1% overestimation by Niatel *et al.*[3] or by Boutillon[5] of the W/e value determined by using this chamber. The newly determined value is $33.61 \pm 0.23\%$ J/C if ICRU Report No. 37 stopping powers are used to evaluate the graphite/air stopping-power ratio. This W/e value is consistent with the second value determined by Niatel *et al.* if one takes into account the recent changes in the BIPM standard for air kerma (exposure),[14] and is consistent also with the experimental results of Büermann *et al.*[25] based on the comparison of the ionometric measurements and calorimetric measurements. If the extreme value of 86.8 eV for the mean excitation energy for graphite is used to evaluate the graphite stopping power, then the value obtained for W/e is $34.15 \pm 0.23\%$ J/C. Direct measurements of W/e values[2] for low-energy electrons have shown that W/e values approach a constant value very close to 34 J/C. It is reasonable to believe that the value of W/e remains constant for higher energies, this suggests that a higher I value may be more appropriate than that used in ICRU Report No. 37. An analysis of five measured I values suggests a weighted mean value of 84.5 ± 5 eV where the uncertainty has the same meaning as in ICRU Report No. 37. Note that only the W/e values determined by using the BIPM graphite flat cavity ion chamber need to be changed by 1.2%, if the graphite/air stopping-power ratio remains unchanged. However, the current standard value of W/e must also be reevaluated since this chamber's determination contributes a significant weight in the final adopted value of W/e; and many of the contributions of experimental determinations of W/e values are in fact correlated. A change in the W/e value would also imply a change of the primary standards for the determination of air-kerma rate in ^{60}Co beams and low-energy x-ray beams.

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