Uncertainties in the ^{60}Co graphite to air stopping-power ratio and a re-evaluation of $(W/e)_{\rm air}$ values

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Abstract

Uncertainties are estimated on the quantities $\rm s_{gr,air}$ in a ^{60}Co beam, $\left(\frac{W}{e}\right)_{\rm air}$ for electrons in dry air and their product. The uncertainty for $\rm s_{gr,air}$ is found to be at least 0.7% (1σ), primarily on account of the large uncertainty in the I-value for graphite recommended by ICRU Report 37 and the large discrepancies with recent high-quality measured values. The previous data on $\left(\frac{W}{e}\right)_{\rm air}$ are re-evaluated and 5 values are changed in view of new physical data or theoretical work and uncertainty estimates are revised. In averaging the experimental results, a method of including correlations between the various measurements is used which is more transparent than that used previously and which takes into account the scatter in the various determinations. The re-evaluated average value of $\left(\frac{W}{e}\right)_{\rm air}$ is 33.89 J/C which is a 0.24% decrease from the currently recommended value. The uncertainty is $\pm$0.13 J/C ($\pm$0.38%) if being used alone. However the uncertainty on the product of $\left(\frac{W}{e}\right)_{\rm air}\rm s_{gr,air}$ is much less, $\pm$0.07 J/C ($\pm$0.21%). The value of the product $\left(\frac{W}{e}\right)_{\rm air}\rm s_{gr,air}$ is shown to depend almost entirely on graphite calorimeter measurements. A detailed re-analysis of 11 papers reporting $\left(\frac{W}{e}\right)_{\rm air}$ values is presented in an appendix.

[This was revised in 2016 to include hyperlinks to figures and from table of contents. Color was added to the figures. No numbers were changed.]

Contents

1 Introduction

The quantities $s_{\rm gr,air}$, the Spencer-Attix graphite to air stopping-power ratio in a ^{60}Co beam; $\left(\frac{W}{e}\right)_{\rm air}$, the energy deposited in dry air as an electron slows down; and their product $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$, play important roles in radiation dosimetry. Using graphite-walled cavity ion chambers, air kerma is established as:

$$K_{\rm air} = \frac{Q_{gas}}{m_{air}} \left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air} \left(\frac{\overline{\mu_{\rm en}}}{\rho}\right)^{\rm air}_{\rm gr} K_{\rm h} K/(1-\overline{g}) \qquad ({\rm Gy}), \tag{1}$$

and exposure is established as:

$$X = \frac{Q_{gas}}{m_{air}} s_{\rm gr,air} \left(\frac{\overline{\mu_{\rm en}}}{\rho}\right)^{\rm air}_{\rm gr} K_{\rm h} K \qquad ({\rm C/kg}), \tag{2}$$

where the various factors have their standard meanings(see [1] for detailed definitions.) Thus the air-kerma standards depend directly on the product $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$ whereas the exposure standards depend on $s_{\rm gr,air}$. Low-energy air-kerma standards based on measurements with free-air chambers depend directly on $\left(\frac{W}{e}\right)_{\rm air}$ whereas low-energy exposure standards are independent of both quantities.

If an exposure or air-kerma calibrated ion chamber is used with a dosimetry protocol, then "in principle" the final assigned dose depends on $\left(\frac{W}{e}\right)_{\rm air}$ since the cavity gas calibration factor ($N_{\rm gas}$ or $N_{\rm D}$) is given by:

$$N_{\rm gas} = \left(\frac{W}{e}\right)_{\rm air} / m_{\rm air} \tag{3}$$

which is clearly independent of $s_{\rm gr,air}$ (where effects of variations in humidity have been ignored, see [1]). However, in practice, when determining $N_{\rm gas}$ using an exposure or air-kerma calibration factor for a user's chamber of wall material called wall, one has:

$$N_{\rm gas} \propto \frac{N_{\rm X} \left(\frac{W}{e}\right)_{\rm air}}{s_{\rm wall,air}} \propto \frac{s_{\rm gr,air} \left(\frac{W}{e}\right)_{\rm air}}{s_{\rm wall,air}} \tag{4}$$

Thus in practice, clinical dosimetry does depend on the product $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$. In the special, but common case of the user's chamber wall being graphite, the quantity $s_{\rm gr,air}$ cancels out (except for a small dependence on chamber size and Δ) and $N_{\rm gas}$ depends only on $\left(\frac{W}{e}\right)_{\rm air}$.

Some primary standards for absorbed dose also depend on the product $\left(\frac{W}{e}\right)_{\rm air}$ $s_{\rm gr,air}$. For example the BIPM's ionometric standard for the absorbed dose to graphite depends on this product[2] as does the BIPM's absorbed dose to water standard which is based on a graphite cavity chamber in a water phantom[3].

These quantities play a central role in radiation dosimetry and for this reason it is worth reviewing our knowledge of these quantities, and in particular the uncertainties on them. This report starts with a review of the uncertainties on the stopping-power ratio $s_{\rm gr,air}$ and concludes that it is a factor of at least two larger than used at the BIPM and elsewhere. This effects the evaluation of $\left(\frac{W}{e}\right)_{\rm air}$ and hence a new evaluation is done, along with a detailed review of 11 of the original papers, updating several of the experimental values in view of more recent values for physical parameters such at $\tau_{\frac{1}{2}}$ for ^{35}S or recent advances in ion-chamber theory.

As has been indicated previously by Svensson and Brahme[4], this report will show quantitatively that the value of the product $\left(\frac{W}{e}\right)_{\rm air}$ $s_{\rm gr,air}$ depends almost entirely on measurements using graphite absorbed-dose calorimeters.

2 Stopping-Power Ratios

To estimate the uncertainty on $s_{\rm gr,air}$ for a ^{60}Co beam, several points need consideration.

The first point is that calculation of stopping-power ratios involves the use of complex electron transport Monte Carlo codes. If the same stopping power data are used, different Monte Carlo codes give results which generally agree within 0.1% and often much better at ^{60}Co energies (see *e.g.* the comparisons in ref [5, 6, 7]). Thus we can assume the calculations themselves contribute negligible uncertainty to the calculated stopping-power ratios.

The second point is that uncertainties in stopping power data are reflected almost directly as uncertainties in the calculated stopping-power ratios (see [8]). Although Andreo and Fransson disagree with this conclusion[9] based on their estimation of the uncertainties, I have argued previously that in general their methods ignore the obviously correlated nature of the uncertainties in stopping powers[8]. However, this disagreement does not arise in the specific case of uncertainties in stopping powers caused by uncertainties in mean excitation energies, I.

The third point is that the uncertainty on the stopping power of graphite is unusually large because of the uncertainties on the I-value assigned in ICRU Report 37 [10]. In Table 4.3 of Report 37, the value I=78.0±7 eV(±9%) is given. On page 19, footnote 10 of that ICRU Report, the stated uncertainty in Table 4.3 is given as corresponding to a 90% confidence level. Thus a 68% confidence level is roughly 4 eV (±5%). Figure 1 shows the corresponding change in the graphite collision stopping power as a function of energy (based on the dlogS/dlogI = dS/S / dI/I values tabulated in the main tables of ICRU 37). The 68% confidence level uncertainty in the stopping power due to uncertainty in the I value of graphite is taken as equivalent to this change. The corresponding uncertainty in the air stopping-power is also shown in the figure based on the I value of 85.7±1.7 eV(90%) given in Table 5.6 of ICRU Report 37 (Δ I= 1% at 68% confidence). Stopping-power ratios in ^{60}Co beams are given accurately by the ratios of stopping powers at 300 keV and I assume that the uncertainties in these values give a reasonable estimate of the uncertainty in the stopping-power ratio. This implies an uncertainty in $s_{\rm gr,air}$ of $\sqrt{0.55^2 + 0.12^2} = 0.56\%$ (68% confidence) due to the uncertainty in the I-values alone.

Figure 1 also shows the change in the graphite stopping power if Bichsel's recently reported, highly accurate value of I=86.9±1.2 eV[11] is used instead of the value of 78 eV reported in ICRU Report 37[10] (the stopping power actually decreases). The new value of the stopping-power ratio implied using this I value would be 1.2% smaller than currently used. This is a major change which confirms the necessity of at least increasing the uncertainty in $s_{\rm gr,air}$ and possibly revising the value itself downward by 1.2% at some point in the future.

As well as the uncertainties from I-value considerations, there are other systematic uncertainties in the graphite collision stopping power. To calculate the density effect correction to the stopping power of graphite, one needs to know the effective density. The problem is that graphite is a very granular material and its bulk density (1.7 to 1.8 g/cm^3) is significantly different from the density in each grain (2.26 g/cm^3). It is even possible that the periodic nature of the grains will affect the calculation of the density effect. There has been some work done on this problem and although a theoretical framework has been developed, no actual numerical results are available[12]. Thus we have no real knowledge of what to do in this case. The value of $s_{gr,air}$ in a ^{60}Co beam varies from 1.0021 for ρ=1.7 g/cm^3 to 0.9998 for ρ = 2.26 g/cm^3[8]. As an absolute minimum we should adopt the mid-point value and assign an uncertainty of 1/2 the range in values, *viz.* ±0.1%. Note that this uncertainty is not that associated with the uncertainty in the bulk density (which is negligible), but is related to the underlying uncertainty in the theory.

The final uncertainty is related to the overall uncertainty in the calculation of the density effect. Between the 1964 and 1984 evaluations of stopping powers, there was no change in the I values for graphite but for 300 keV electrons the collision stopping power changed by 0.7% due to a change in how the density effect was evaluated (see fig 2). I believe that this change leaves a residual uncertainty in the final value which is about 1/2 of the latest change *i.e.* ±0.35% for ^{60}Co beams (68%). This uncertainty is comparable to the 0.4% variations in the stopping power of water calculated using two alternative theoretical formulations of the density effect[10].

Table 1 summarizes the uncertainty estimates on $s_{gr,air}$ and compares them to those used by others. The total uncertainty on the graphite to air stopping-power ratio in a ^{60}Co beam is ±0.7%. It is clear that the proposed uncertainty estimates are much greater than those currently used in most cases.

This increased uncertainty may not directly affect air-kerma standards based on cavity ion chambers since they depend on the product $\left(\frac{W}{e}\right)_{air} s_{gr,air}$, but it will affect ion-chamber-based exposure standards and it will also affect the choice of $\left(\frac{W}{e}\right)_{air}$ values since the uncertainty on $s_{gr,air}$ will affect the weighted averaging procedures.

3 Re-evaluation of $\left(\frac{W}{e}\right)_{air}$ data

Given the importance of the quantities $\left(\frac{W}{e}\right)_{air}$ and $\left(\frac{W}{e}\right)_{air} s_{gr,air}$, it is worth reviewing our knowledge of them. I have started from the 1987 paper by Boutillon and Perroche-Roux which is the basis of the currently recommended value of $\left(\frac{W}{e}\right)_{air} = 33.97 \pm 0.05$ J/C(1σ)[13]. To average the data their paper uses a sophisticated method which includes consideration of correlations in various experimental values.

I have done the averaging using weighted least squares fitting, in one case ignoring correlations and in another case using a less general but I believe accurate method to estimate the effects of the major correlations. The technique is more transparent and can include consideration of the scatter in the data in determining the uncertainties. It is restricted to the case where only one type of correlation exists between any two data points. Thus data with correlations because of both stopping-power ratios and mass-energy absorption coefficients are not properly accounted for. However, since the correlation of most interest is that due to stopping-power ratios, this technique should be adequate(see Appendix B).

If correlations are ignored, there are two uncertainties to consider for each determination of $\left(\frac{W}{e}\right)_{\rm air}$ - a larger one which includes the uncertainty on $s_{\rm gr,air}$ where appropriate and a smaller one which does not include the uncertainty on $s_{\rm gr,air}$. For a subset of experiments, because of the actual experimental methods used, this latter uncertainty corresponds (to first order) to the uncertainty on the measured product $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$.

3.1 Re-Analysis of BIPM Evaluated Data Set

I have reanalyzed the original BIPM data set of Boutillon and Perroche-Roux to allow separation of the effects of changes in how the weighted averaging is done and the effects of the re-analysis of the original data which is discussed below. As seen in Table 2, doing a simple (*i.e.* uncorrelated) weighted least squares average of the entire BIPM data set gives almost identical results to those of Boutillon and Perroche-Roux if the original "large" uncertainties are considered($\left(\frac{W}{e}\right)_{\rm air}$=33.98(6) vs 33.97(5) J/C, where the value in brackets gives the 68% confidence limit for the last digit, see Appendix B and ref [14] for a complete discussion of assigning uncertainties). Since Boutillon and Perroche-Roux utilize the same larger uncertainties for their "on-diagonal" variances, this similarity of results implies that i) consideration of correlations using their method has little effect on the $\left(\frac{W}{e}\right)_{\rm air}$ value and ii) their consideration of correlations does not substantially increase the overall uncertainty (in this case, the internal uncertainty is ±0.04 J/C and I assume consideration of correlations by Boutillon and Perroche-Roux increased this estimate to ±0.05).

Using the technique outlined in Appendix B, correlated uncertainties in the stopping-power ratios included in the original data can be included in the analysis in two ways. If the final goal is a value of $\left(\frac{W}{e}\right)_{\rm air}$, then the 0.3% correlated uncertainty in the stopping-power ratios must be applied to all those measurements which actually measured the product $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$. In this case the value determined is 33.92(7) J/C which is lower than the value determined by Boutillon and Perroche-Roux and has a somewhat larger uncertainty. Here, only 39% of the weight comes from the calorimeter vs cavity ionization measurements (papers 9 through 14). If the final goal is a value of $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$, it is more appropriate to assign the 0.3% correlated uncertainty to all the measurements which do not measure the product. This causes little change in the average value of $\left(\frac{W}{e}\right)_{\rm air}$ (33.93) but does reduce the uncertainty to the same value obtained by Boutillon and Perroche-Roux. In this analysis of the original Boutillon and Perroche-Roux data, 96.5% of the weight goes to the calorimeter based measurements.

Figure 3 presents the data of Boutillon and Perroche-Roux along with the weighted averages determined with the large or small uncertainty estimates.

Thus, if all that were done were to use the averaging techniques described here, the data presented by Boutillon and Perroche-Roux would imply a slight reduction in the value of $\left(\frac{W}{e}\right)_{\rm air}$ and a slight increase in its uncertainty to 33.92(7) J/C.

3.2 Re-analysis of Original Measurements

As well as developing other averaging techniques, the original $\left(\frac{W}{e}\right)_{\rm air}$ data have been re-analyzed. I start from the work of Boutillon and Perroche-Roux[13] and accept the need to re-analyze using dry air data and consistent ICRU Report 37 stopping powers. I have re-examined the individual uncertainty estimates used by Boutillon and Perroche-Roux (discussed individually below) and have globally assigned a ±0.7% uncertainty on the value of $s_{\rm gr,air}$. I have also found that the values in several of the papers needed to be updated to reflect more recent data (such as the half-life of ^{35}S). The following briefly draws attention to the important points concerning each of the 11 papers which are discussed in detail in Appendix A. Table 3 summarizes the present estimates compared to those of Boutillon and

Perroche-Roux. Four of the original papers (#4, 5, 6 and 8) were not considered because they had such large uncertainties.

Paper 1: Bay *et al.* (1957,^{35}S,β)[15]

I assign a larger uncertainty because there is an 0.3%(1σ) uncertainty from the half-life correction alone. I also believe the original 0.3% uncertainty on the energy output should be treated as 1σ. In fact this uncertainty should probably be higher because no estimate of the thermal heat defect nor its uncertainty was included. Although not considered by Boutillon and Perroche-Roux, there is a strong correlation between the values of $\left(\frac{W}{e}\right)_{\rm air}$ in papers 1 and 2 because of the use of a common measurement of source output. Finally, there was a 4 half-life correction used in this measurement and the best estimate of $\tau_{1/2}$ has changed since 1957. This change in $\tau_{1/2}$ implies a 0.9% decrease in the measured value of $\left(\frac{W}{e}\right)_{\rm air}$.

Paper 2: Gross *et al.*(1957, ^{35}S, β) [16]

Note the correlation with paper 1 as discussed above, and the uncertainty in the energy output as discussed above as well. Boutillon and Perroche-Roux assumed the uncertainties in this paper were 3σ but from table 1 of Gross *et al.*, one can calculate the rms deviation on the measurements, and this is the value reported in the uncertainty table, *i.e.* these are 1σ uncertainties. Therefore I assume the rest of the uncertainties were 1σ estimates as well. I don't feel comfortable with the 15% correction for the use of an aluminum electrode in the extrapolation chamber.

Paper 3: Jesse(1958, ^{35}S, β)[17, 18]

I have assumed the original uncertainties were 1σ, not 2σ as assumed in Boutillon and Perroche-Roux.

Paper 7: Myers *et al.*(1961,^{60}Co) [19, 20]

Their experimental method uses the decay scheme of ^{60}Co, the estimates of which have changed since 1961. I reduce the value of $\left(\frac{W}{e}\right)$ by 0.2% to reflect this change. Hubbell gives $\pm$1% on $\left(\frac{\mu_{\rm en}}{\rho}\right)$ values which he tells me is like the uncertainty estimates in ICRU Report 37, *i.e.* 90% confidence intervals. There have been many corrections to the data in Myers *et al.*'s paper. Taken together there seems to be good reason to retain the original $\pm$1% uncertainty. Note also that this method uses the free air chamber estimate of NIST's exposure rate –

and this is 1.2% less than their cavity ion chamber estimate [21] and these are low by a further 0.9% based on our recent work on wall corrections[22], *i.e. if* we were to use the corrected values of the NIST exposure based on ion chambers (which is after all NIST's primary standard), the value of $\left(\frac{W}{e}\right)_{\rm air}$ measured in this experiment would decrease by 2.1% –however the original data are used here.

Paper 9: Bewley (1963, ^{60}Co)[23]

Bewley did not correct for cavity perturbation for his ion chamber measurements in phantom. Using the BIPM value for this correction [2] I increased $\left(\frac{W}{e}\right)_{\rm air}$ by 0.5%.

Paper 10: Petree and Lamperti (1967, ^{60}Co) [24]

I added 0.2% systematic uncertainty for core attenuation corrections which I consider to be like perturbation corrections.

Paper 11: Engelke and Hohlfeld (1971, ^{137}Cs) [25]

I added 0.2% uncertainty for the K_p correction. I accepted Boutillon and Perroche-Roux's assumption that the original uncertainties were 3σ. No corrections have been made for the gap effect but presumably these should be made.

Paper 12: Guiho and Simoen (1975, ^{60}Co) [26]

I assume that the French exposure standard should be increased by 0.6% as were the other standards [22] to correct for wall attenuation corrections but I do not have the original paper (cited in Guiho and Simoen as to be submitted) describing the French exposure standards

Paper 13: Niatel *et al.* (1985, ^{60}Co, ionometric vs calorimeter) [27]

I added 0.2% uncertainty for the K_p correction. I assumed the gap and uniformity corrections cancelled each other[28].

Paper 14: Kunze and Hecker (1980, ^{60}Co) [29]

I added 0.2% uncertainty for the K_p correction. No corrections have been made for the gap effect but presumably these should be made.

Paper 15: Niatel *et al.*(1985, ^{60}Co, exposure vs activity) [27]

I increased the BIPM value of air-kerma as in ref [22] and used Hubbell's estimate of the uncertainty on $\left(\frac{\mu_{\rm en}}{\rho}\right)$.

From Table 2 it can be seen that averaging the 11 NRC revised data values without accounting for correlations decreases $\left(\frac{W}{e}\right)_{\mathrm{air}}$ values slightly compared to corresponding averages of the 11 original data values of Boutillon and Perroche-Roux. The uncertainties assigned are somewhat larger and the χ^2/df is somewhat smaller. If a value for $\left(\frac{W}{e}\right)_{\mathrm{air}}$ is extracted including a consideration of the 0.7% correlated uncertainty on $s_{\mathrm{gr,air}}$ and the 0.3% correlated uncertainty of the source output between papers 1 and 2, the value becomes somewhat smaller and the uncertainty increases substantially. Because of the large uncertainty on the stopping-power ratio, the papers which do not require $s_{\mathrm{gr,air}}$ carry over 70% of the weight compared to only 40% if the uncertainty on $s_{\mathrm{gr,air}}$ is taken as 0.3% as done by Boutillon and Perroche-Roux. If the correlation between papers 1 and 2 is ignored, the value deduced for $\left(\frac{W}{e}\right)_{\mathrm{air}}$ is unchanged but the uncertainty decreases somewhat.

If the product $\left(\frac{W}{e}\right)_{\mathrm{air}} s_{\mathrm{gr,air}}$ is extracted from the data and stopping-power ratio correlations are taken into account (*i.e.* a correlated uncertainty of 0.7% is added to the uncertainty in papers 1, 2, 3 and 7), then the corresponding value of $\left(\frac{W}{e}\right)_{\mathrm{air}}$ is 33.91(7) J/C. In this case 98% of the weight comes from the papers measuring $\left(\frac{W}{e}\right)_{\mathrm{air}} s_{\mathrm{gr,air}}$ (*viz.* papers 9 to 15, all of which used graphite calorimeters except paper 15 which carries only 5% of the weight). If the BIPM uncertainty of 0.3% on $s_{\mathrm{gr,air}}$ is used, the value and uncertainty on $\left(\frac{W}{e}\right)_{\mathrm{air}} s_{\mathrm{gr,air}}$ does not change because over 95% of the weight is still from the $\left(\frac{W}{e}\right)_{\mathrm{air}} s_{\mathrm{gr,air}}$ measurements.

3.3 Conclusions re $\left(\frac{W}{e}\right)_{\mathrm{air}}$

Based on this re-analysis, the best estimate of $\left(\frac{W}{e}\right)_{\mathrm{air}}$ is 33.88(13) J/C and the best estimate of $\left(\frac{W}{e}\right)_{\mathrm{air}}$ to be used as a product with $s_{\mathrm{gr,air}}$ is 33.91(7) J/C. These are 0.27% and 0.18% less than the currently accepted value of 33.97(5) J/C and imply a 0.27% decrease in all air-kerma standards based on free air-chambers and a corresponding 0.18% decrease in air-kerma standards based on graphite ion chambers and absorbed-dose standards based on cavities in graphite. The major reasons for the differences are how the averaging is done and the fact that 4 of the 5 changes in the evaluated $\left(\frac{W}{e}\right)_{\mathrm{air}}$ values decrease the measured value. The values of the uncertainties on the average values have also increased, substantially in the case of the value of $\left(\frac{W}{e}\right)_{\mathrm{air}}$ alone (from ±0.15% to ±0.38%). This will significantly affect the uncertainty on all air-kerma standards based on free air chambers. Recall that these estimates of the uncertainty are known to be underestimates because multiple correlations between various experiments have been ignored (see Appendix B). In contrast, the uncertainty in standards based on cavities in graphite increases only slightly because these use the product $\left(\frac{W}{e}\right)_{\rm air}$ $s_{\rm gr,air}$.

Another conclusion is that high caliber $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$ values depend almost entirely on graphite calorimeter measurements. These values (from papers 9 to 14) carry 93% of the weight in determining $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$ (or 90% using the BIPM estimate of 0.3% uncertainty on the value of $s_{\rm gr,air}$.) This implies that standards based on graphite-cavity ionization measurements are also based on graphite calorimeters(see below).

One disquieting feature of the analysis is that the χ^2/df values for the $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$ values are all large and highly unlikely – suggesting further systematic errors.

There are 3 high quality values of $\left(\frac{W}{e}\right)_{\rm air}$ measured independently of stopping-power ratios (papers 1,3 and 7). Two of the three use ^{35}S β particles ($\overline{E}$ = 49 keV) which may have $\left(\frac{W}{e}\right)_{\rm air}$ differing from the value for $\left(\frac{W}{e}\right)_{\rm air}$ in a ^{60}Co beam. Other evidence that $\left(\frac{W}{e}\right)_{\rm air}$ is independent of electron energy is not good enough to make statements about constancy at the 1% or better level. Two of these measurements have required major revisions (paper 1 for a new half-life correction and paper 7 for a new value of $\left(\frac{\mu_{\rm en}}{\rho}\right)$) and paper 7 uses a free-air-chamber value of exposure rate at NIST which is 1.2% lower than the exposure rate derived using ion chambers[21]. Thus, these data cannot be used to estimate or verify the value of $s_{\rm gr,air}$ to any higher accuracy than the theoretical uncertainty.

These results suggest adopting a value of $\left(\frac{W}{e}\right)_{\rm air}$ = 33.89 J/C which is 0.24% less than the currently recommended value[13]. For situations in which it is used in combination with $s_{\rm gr,air}$ in a ^{60}Co beam, the uncertainty on the product should be ±0.07 J/C (=0.21%). For situations in which $\left(\frac{W}{e}\right)_{\rm air}$ is required on its own, the uncertainty is ±0.13 J/C (=0.38%).

4 Implications for Primary Standards and Conclusions

These results have significant impact on many primary standards.

Air-kerma standards based on free-air chambers decrease in value by 0.24% because of the decrease in $\left(\frac{W}{e}\right)_{\rm air}$ and their uncertainties must increase substantially to account for the 0.38% uncertainty in $\left(\frac{W}{e}\right)_{\rm air}$ which increased because of the increased uncertainty in $\rm s_{gr,air}$. There is no corresponding change in exposure standards based on free-air chambers.

Air-kerma standards based on graphite-walled ion chambers all decrease by 0.24% as well, although the increase in uncertainty due to the increase in uncertainty in $\left(\frac{W}{e}\right)_{\rm air}\rm s_{gr,air}$ is quite small (from 0.15% to 0.18%). In contrast, exposure standards based on graphite-walled ion chambers do not change in value but their uncertainties increase substantially because of the increase in the uncertainty on $\rm s_{gr,air}$ to 0.7%.

Absorbed-dose standards based on charge measurements in graphite cavities decrease by 0.24% because they depend on $\left(\frac{W}{e}\right)_{\rm air}\rm s_{gr,air}$.

One major implication of these findings is that all standards which utilize the product $\left(\frac{W}{e}\right)_{\rm air}\rm s_{gr,air}$ are based on graphite absorbed-dose calorimeters since over 90% of the weight for the values included in the averaging process is from measurements with absorbed dose calorimeters. Thus, as pointed out previously[4] graphite calorimeters are an essential part of air-kerma standards based on graphite-walled ion chambers .

The current work has not utilized the recently reported I values for graphite but if this value were to be accepted the value of $\rm s_{gr,air}$ in ^{60}Co beams would decrease by 1.2% and this would imply a substantial increase in the value of $\left(\frac{W}{e}\right)_{\rm air}$ - up to 0.7% if one assigns a low uncertainty to the new value of $\rm s_{gr,air}$.

The final conclusion is that individual values of $\rm s_{gr,air}$ and $\left(\frac{W}{e}\right)_{\rm air}$ are subject to considerable fluctuation and are not as well known as one would like. To have standards which avoid constant revisions requires that they use the product $\left(\frac{W}{e}\right)_{\rm air}\rm s_{gr,air}$ which is well known. However, using this value, which depends mostly on graphite calorimeters, implies conceptually complicated primary standards.

5 Tables and Figures

Table 1:
Components of uncertainty on $s_{gr,air}$ in ^{60}Co beams based on the uncertainties in the stopping powers at 300 keV. All uncertainties refer to 68% confidence limits.

Source	$\Delta s_{gr,air}$	comment
Δ I_{gr}	0.55%	stated ICRU uncertainty
Δ I_{air}	0.12%	stated ICRU uncertainty
Δ bulk vs grains	0.1%	1/2 of range
Δ density effect	0.35%	1/2 of last change
Total	0.67%	0.6% just I uncertainties
Values in use		
NRC	0.5%	Based on a "guess"
NIST	0.25%	ref[21] gave 2σ=0.5%
BIPM	0.2%	ref[27]
ARL	0.3%	CCEMRI(I)/85–10

Table 2:
Summary of results for $\left(\frac{W}{e}\right)_{\mathrm{air}}$ re-evaluations. Figures in brackets are 68% confidence intervals for the last digit. The P values are the probabilities that such large χ^2/df occur by chance.

Description	$\left(\frac{W}{e}\right)_{\mathrm{air}}$ large uncert		$\left(\frac{W}{e}\right)_{\mathrm{air}} s_{\mathrm{gr,air}}$– small uncert	
	$\left(\frac{W}{e}\right)_{\mathrm{air}}$ J/C	χ^2/df	$\left(\frac{W}{e}\right)_{\mathrm{air}}$ J/C	χ^2/df
original BIPM 15	33.97(5)			
BIPM all 15, no correlations	33.98(6)	1.8(P≈5%)	33.94(4)	3.0(P<0.01%)
BIPM $\left(\frac{W}{e}\right)_{\mathrm{air}} s_{\mathrm{gr,air}}$+0.3% corr	–		33.93(5)	3.0(P<0.01%)
BIPM $\left(\frac{W}{e}\right)_{\mathrm{air}}$+0.3% corr			33.92(7)	1.9(P≈2%)
BIPM (NRC 11, no corr)	33.97(7)	2.0(P≈3%)	33.93(5)	3.6 (P< 1%)
NRC all 11, no corr	33.93(9)	1.2(P≈30%)	33.91(6)	2.4(P≈1%)
NRC $\left(\frac{W}{e}\right)_{\mathrm{air}}$ +0.7%spr,0.3% out[b)]	–		33.88(13)[b)]	1.2(P≈30%)
NRC $\left(\frac{W}{e}\right)_{\mathrm{air}} s_{\mathrm{gr,air}}$+0.7% spr			33.91(6)	1.9(P≈5%)

[a)] papers determining $\left(\frac{W}{e}\right)_{\mathrm{air}} s_{\mathrm{gr,air}}$ are 6, 8 – 15 and all but papers 6 and 15 used graphite absorbed-dose calorimeters.
[b)] Values don't change if the correlation between papers 1 and 2 is ignored but the uncertainty is reduced to ±0.12 J/C.

Table 3:
Summary of current evaluated results and previous results from the BIPM [13].

No.	Description	BIPM			NRC		
		$\left(\frac{W}{e}\right)_{air}$ J/C	uncertainty		$\left(\frac{W}{e}\right)_{air}$ J/C	uncertainty	
			without $s_{gr,air}$	with		without $s_{gr,air}$	with
1	^{35}S,β	33.9	–	0.13	33.6	–	0.21
2	^{35}S,β	34.63	0.16$^{a)}$	0.19	34.63	0.25$^{a)}$	0.33
3	^{35}S,β	33.9	–	0.17	33.9	–	0.34
7	X, E out	33.92	–	0.15	33.85	–	0.34
9	cal,cav	34.21	0.21	0.23	34.38	0.22	0.32
10	cal,cav	33.80	0.05	0.11	33.80	0.08	0.24
11	cal,cav	33.87	0.06	0.12	33.87	0.09	0.24
12	cal,X	34.02	0.10	0.14	33.82	0.11	0.26
13	cal,cav	33.96	0.04	0.11	33.96	0.08	0.25
14	cal,cav	34.27	0.15	0.18	34.27	0.16	0.27
15	X,Act	33.81	0.12	0.16	33.73	0.17	0.29

$^{a)}$ $s_{water,air}$

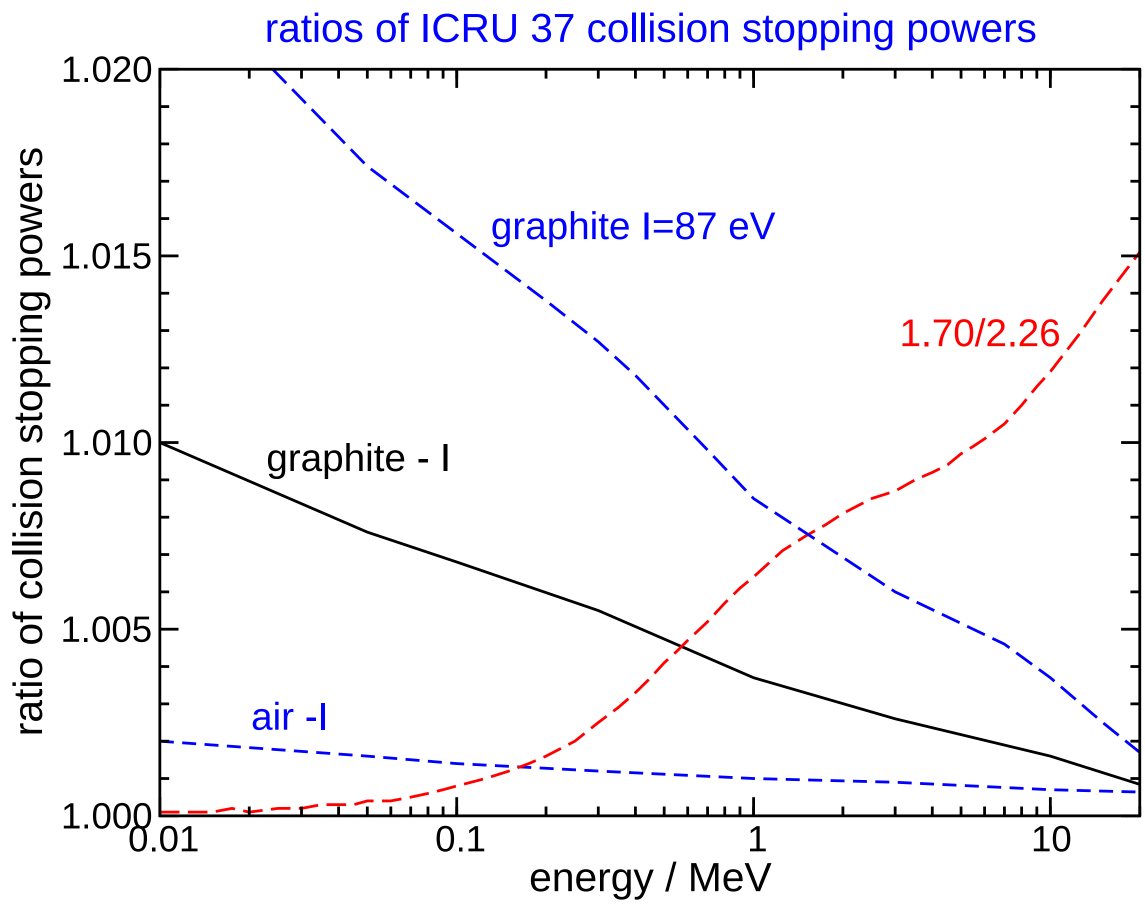

Figure 1: Changes in graphite and air collision stopping powers for one standard deviation changes in the I value (using uncertainties assigned in the ICRU 37 Report). Also shown is the ratio of collision stopping powers for graphite calculated assuming a density of 1.70 g/cm^3 or 2.26 g/cm^3. The dot-dash line shows the size of the change in graphite stopping power implied by the recently reported value of I=87 eV[11], although the actual change would decrease the stopping power.

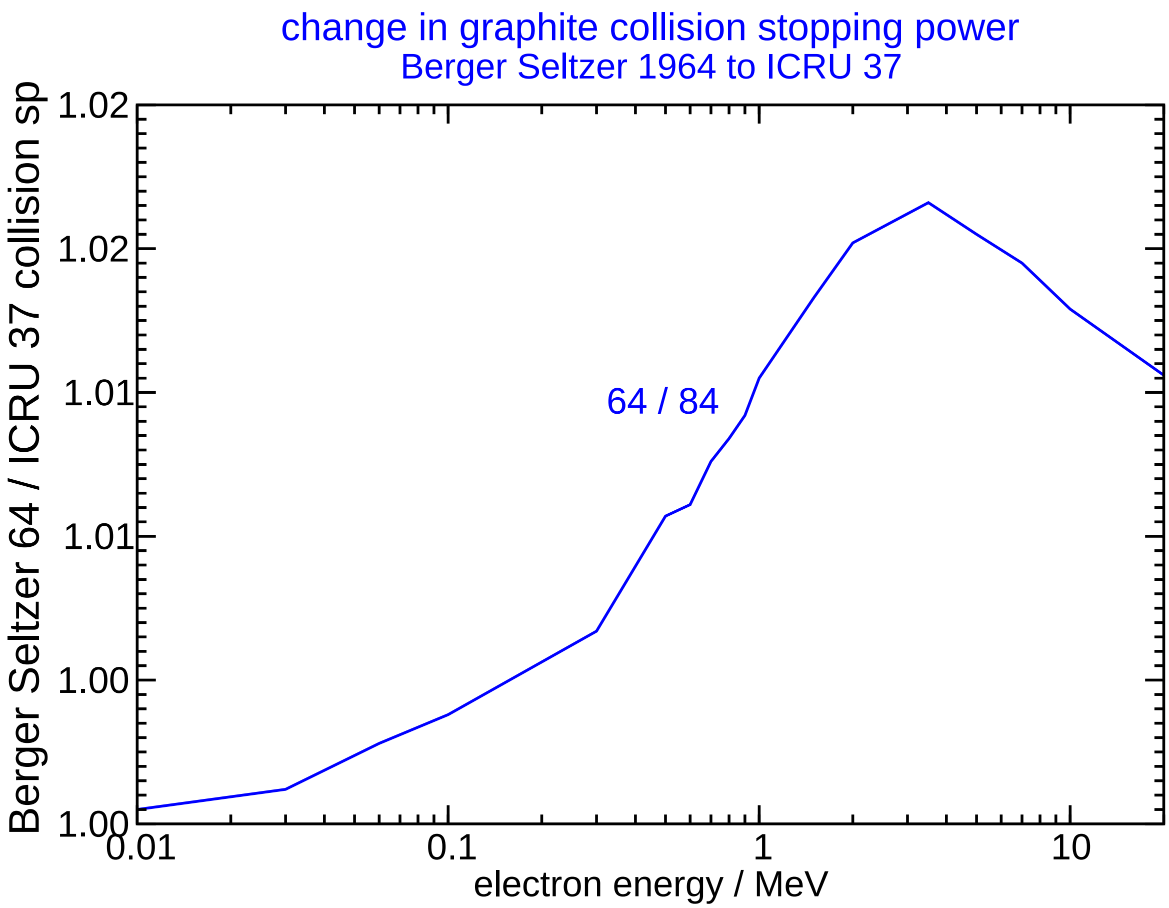

Figure 2: Change in graphite collision stopping power from 1964 compilation of Berger and Seltzer to ICRU 37 Report in 1984.

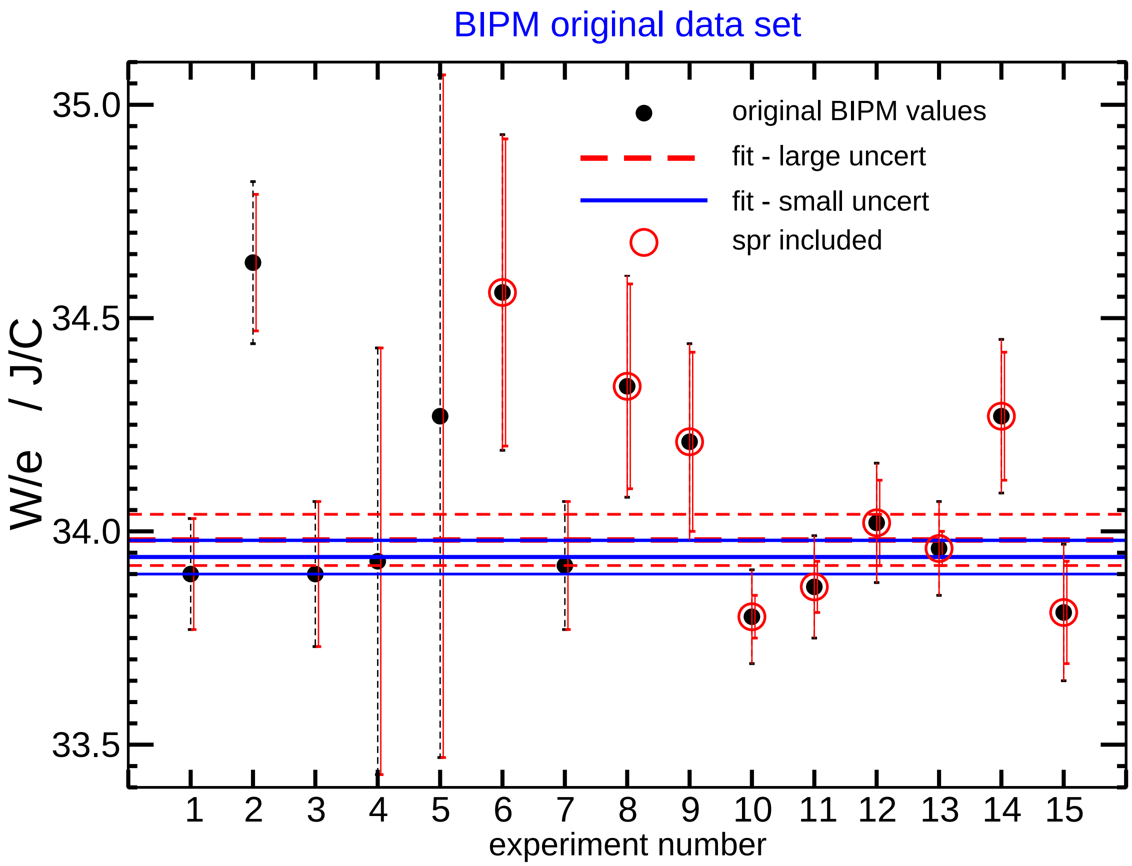

Figure 3: Original data as analyzed by Boutillon and Perroche-Roux[13]. Averages shown correspond to fits with no correlations, weighting with the large uncertainties gives 33.98(6) J/C or weighted by the small uncertainties gives 33.94(4) J/C.

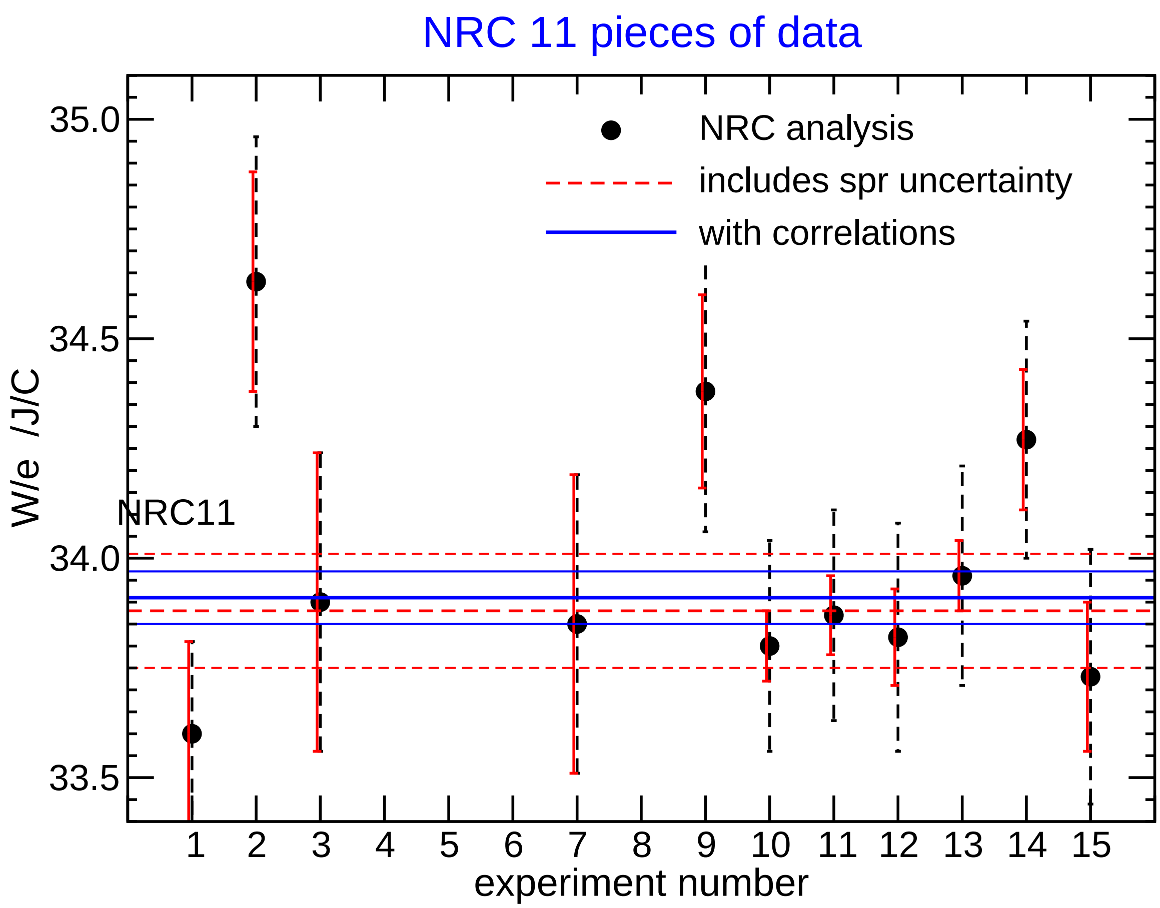

Figure 4: $\left(\frac{W}{e}\right)_{\rm air}$ data as reanalyzed here. Average values shown are for correlated weighted fits, in one case for the value of $\left(\frac{W}{e}\right)_{\rm air}$ (33.88(13)) and the other when used as part of the product with $s_{\rm gr,air}$(33.91(6) J/C).

6 Appendix A: Review of Papers Used to Determine $\left(\frac{W}{e}\right)_{\rm air}$

6.1 Paper 1

Z. Bay, W.B. Mann, H.H. Seliger and H.O. Wyckoff, **Absolute Measurement of W_{air} for sulfur-35 Beta Rays**, Rad'n. Res. **7** (1957) 558 – 569.

Table 4:

	$\left(\frac{W}{e}\right)_{\rm air}$ (J/C, eV/ip)	uncertainty		comments
		J/C	%	
reported	33.7	0.3	0.7%	
ICRU	33.9			
B&PR	33.9	0.13	0.4%	
NRC	33.6	0.21	0.6%	modern τ ⇒0.9% decrease

Method:
Measure energy out of source of ^{35}S (0.3%) using calorimeter comparison to other known sources and measure total current from source mounted on thin film in a container.

$$E_{out} = \left(\frac{W}{e}\right) I$$

Needed 4 half-life correction for source decay. Used 87.16 days, now 87.44±0.07 days (1σ) so uncertainty from half-life alone is ±0.3%. Change causes 0.9% decrease in measured W.

Note that this paper is strongly correlated to paper 2 since both use the same measured source output power. Note also that the measure of source output also appears to assume there is no thermal heat defect for electrons slowing in $NaSO_4$ and/or glass. It is not clear this can be proven at the 1% level.

Weights

for $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$: 1%
for $\left(\frac{W}{e}\right)_{\rm air}$: 33%

6.2 Paper 2

W. Gross, C. Wingate and G. Failla, **Average Energy Lost by Sulfur-35 Beta Rays per Ion Pair Produced in Air**, Rad'n Res. **7** (1957) 570 – 580.

Table 5:

	$\left(\frac{W}{e}\right)_{\text{air}}$ (J/C, eV/ip)	uncertainty J/C	uncertainty %	comments
reported	33.6	0.3	1.0%	0.7% from spr, 1σ
			0.6%	
ICRU	33.83			
B&PR	34.63	0.16	0.5%	assumed orig 3σ
		0.19	0.6%	
NRC	34.63	0.25	0.74%	theirs no s
		0.33	1.0%	0.7% on s

Method:
Used sol'n of ^{32}S of known activity in an extrapolation chamber and used Bragg-Gray theory.

$$E_{out} = \left(\frac{W}{e}\right) N \left(\frac{\overline{L}}{\rho}\right)_{\text{air}}^{\text{water}}$$

where N is Q/s/g of air (from measured I) and E_{out} from source power output measurement.

Note that this paper is strongly correlated to paper 1 since both use the same measured source output power and suffers from the same uncertainty re heat defects in the power measurement as mention for paper 1.

Corrected by 15% for Al electrode in water extrapolation chamber using other people's measured results.

I assume the original paper gave 1σ uncertainty estimates. From their Table 1 one can calculate 1σ=0.27% from the data and it is shown in final analysis as 0.3%. So used their values as 1σ.

B&PR increased uncert of backscatter corr. to 0.3% but that is what table says.

Paper uses water/air stopping-power ratio unlike most papers.

Weights

for $\left(\frac{W}{e}\right)_{\text{air}} s_{\text{gr,air}}$: 1%
for $\left(\frac{W}{e}\right)_{\text{air}}$: 12%

6.3 Paper 3

W.P. Jesse, **Absolute Energy to Produce an Ion Pair in Various Gases by Beta Particles from S^{35}.**, Phys. Rev. **109** (1958) 2002 – 2004.

W.P. Jesse and J. Sadaukis, **Absolute Energy to Produce an Ion Pair by Beta Particles From S^{35}**, Phys. Rev. **107** (1957) 766 – 771.

Table 6:

	$\left(\frac{W}{e}\right)_{\text{air}}$ (J/C, eV/ip)	uncertainty J/C	uncertainty %	comments
reported	33.9	0.33	1.0%	
ICRU	33.9			
B&PR	33.9	0.17	0.5%	assumed orig 2σ
NRC	33.9	0.34	1.0%	

Method:
For a source of known activity (±0.74% from Leo Yaffe) and a calculated mean energy (they used 48.7±0.5%, a more recent value is 48.8±0.2% (1σ)), they measure total charge in enclosed box for various gases (not air). Using previously measured W ratios, they deduce W for air.

$$AE_{\text{ave}} = \left(\frac{W}{e}\right) I$$

Table shows stats ±0.29% 1σ. Mean energy now known to have an uncertainty of ±0.2% (1σ, NCRP 58). Authors say estimated probable uncertainty is 1%. Given all the steps and necessity of getting results from elsewhere, I adopt 1%. Dallas Santry of the NRC radioactivity standards lab points out that the activity of ^{35}S would be hard to measure.

Weights

for $\left(\frac{W}{e}\right)_{\text{air}} s_{\text{gr,air}}$: 0.4%
for $\left(\frac{W}{e}\right)_{\text{air}}$: 14%

6.4 Paper 6

P.N. Goodwin, **Calorimetric Measurements on a Cesium-137 Teletherapy Unit**, Rad'n. Res. **10** (1959) 6 – 12.

Table 7:

	$\left(\frac{W}{e}\right)_{\rm air}$ (J/C, eV/ip)	uncertainty J/C	uncertainty %	comments
reported	33.9	0.5	1.5%	s=1.026
ICRU	34.0			
B&PR	34.56	0.36 0.37	1.1% 1.2%	s=1.009
NRC				

Method:
Measured Ψ using a total absorption calorimeter and beam area and measured X at same spot using calibrated ion chamber. ^{137}Cs.

$$X\left(\frac{W}{e}\right) = \Psi\left(\frac{\overline{\mu_{\rm en}}}{\rho}\right)_{\rm air}$$

Uses wrong J/eV (by 1/2%), doesn't give $\left(\frac{\overline{\mu_{\rm en}}}{\rho}\right)_{\rm air}$ and X is not discussed. Stated uncertainty high. Just ignore this one.

Weights

for $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$: 0%
for $\left(\frac{W}{e}\right)_{\rm air}$: 0%

6.5 Paper 7

I.T. Myers, W.H. LeBlanc, D.M. Fleming and H.O. Wyckoff, **An Adiabatic Calorimeter for High Precision Source Standardization**, Rad'n Res. **14** (1961) 488 – 489 (abs).

I.T. Myers, W.H. Le Blanc, D.M. Fleming and H.O. Wyckoff, **An Adiabatic Calorimeter for High Precision Source Standardization and Determination of W(air)**, Report HW-SA-2165-US Dept Commerce (1961) 1 – 15.

Table 8:

	$\left(\frac{W}{e}\right)_{\rm air}$ (J/C, eV/ip)	uncertainty		comments
		J/C	%	
reported	33.84	0.34	1.0%	
ICRU	33.76			
B&PR	33.92	0.15	0.44%	changed muen 0.46%
NRC	33.85	0.34	1.0%	reduce 0.2% from decay 2.1% lower for ion ch.X

Method:
Measured energy output from a ^{60}Co source with a total absorption calorimeter and deduced photon energy fluence using knowledge of decay scheme. Using measured exposure from free-air chamber!

$$X\left(\frac{W}{e}\right) = \Psi\left(\frac{\overline{\mu_{\rm en}}}{\rho}\right)_{\rm air}$$

Using muen for air, they deduce W/e = 33.84±1%.

Current decay scheme gives 96.43% of energy as gammas whereas they used 96.2%. BIPM calculated more accurate mass-energy absorption coefficient and reduced uncertainty.

Hubbell says 1% uncertainty on the coefficient (not a ratio) and this is probably 90%, so assign 0.5% as they did in original paper. Exposure uncertainty is 0.7% and energy output is 0.4%. Even assuming these are NBS 3σ values, gives 1σ as 0.56%. Given other changes, I leave at 1%.

Note that if one used X from NIST's cavity ion chambers, the value of X increases by 1.2% and the implied value of $\left(\frac{W}{e}\right)_{\rm air}$ decreases by this amount. Using Monte Carlo calculated wall corrections for the exposure standard at NIST would further reduce $\left(\frac{W}{e}\right)_{\rm air}$ by 0.9%[22].

Weights

for $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$: 0.4%
for $\left(\frac{W}{e}\right)_{\rm air}$: 14%

6.6 Paper 9

D.K Bewley, **The measurement of locally absorbed dose of megavoltage X-rays by means of a carbon calorimeter**, Brit J Radiol. **36** (1963) 865 – 878.

Table 9:

	$\left(\frac{W}{e}\right)_{\text{air}}$ (J/C, eV/ip)	uncertainty J/C	uncertainty %	comments
reported	33.97	0.21	0.6%	s = 1.004
ICRU	34.14			
B&PR	34.21	0.21	0.6%	s=1.003
		0.23		
NRC	34.38	0.22	0.6%	increase 0.5±0.2% cav pert.
		0.32	0.94%	0.7% spr

Method:
Graphite calorimeter in ^{60}Co beams and then cavity chamber inside graphite phantom.

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)^{\text{gr}}_{\text{air}} = \frac{D}{I/m}$$

Cavity chamber 3cm diam, 5mm thick with 1mm collector - like PTB (0.2%) and BIPM (0.5%) and needs perturbation correction –adopt BIPM value which increases $\left(\frac{W}{e}\right)_{\text{air}}$ by 0.5%.

Paper refers to standard deviation for all uncertainties.

Weights

for $\left(\frac{W}{e}\right)_{\text{air}} s_{\text{gr,air}}$: 4%
for $\left(\frac{W}{e}\right)_{\text{air}}$: 1%

6.7 Paper 10

B. Petree and P. Lamperti, **A Comparison of Absorbed Dose Determinations in Graphite by Cavity Ionization Measurements and by Calorimetry**, J of Res. of NBS, Vol **71C** (1967) 19 – 27.

Table 10:

	$\left(\frac{W}{e}\right)_{\text{air}}$ (J/C, eV/ip)	uncertainty J/C	uncertainty %	comments
reported	33.59	0.14	0.41%	s=1.004
ICRU	33.69			
B&PR	33.80	0.05	0.15%	s= 1.001
		0.11	0.32%	
NRC	33.80	0.08	0.25%	0.2% added
		0.24	0.7%	

Method:
Measured dose in graphite phantom and then placed special spherical ion chamber at the same point.

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)_{\text{air}}^{\text{gr}} = \frac{D}{I/m}$$

Used corrections for special cores and attenuation. Add 0.2% systematic uncertainty. No gap effect correction has been made.

Weights

for $\left(\frac{W}{e}\right)_{\text{air}} s_{\text{gr,air}}$: 25%
for $\left(\frac{W}{e}\right)_{\text{air}}$: 7%

6.8 Paper 11

B.A. Engelke and K. Hohlfeld, **A calorimeter as a standard device to measure absorbed doses and the determination of the mean energy absorbed to generate an ion-pair in air (translated from German)**, PTB Mitteilungen **71** (1971) 336 – 342.

Table 11:

	$\left(\frac{W}{e}\right)_{\rm air}$ (J/C, eV/ip)	uncertainty J/C	uncertainty %	comments
reported	33.72	0.51	1.5%	s=1.0135
		0.17	0.5%	no s uncert
ICRU	33.82			
B&PR	33.87	0.06	0.18%	assumed orig 3σ
		0.12	0.36%	s=1.012
NRC	33.87	0.09	0.27%	added 0.2%
		0.24	0.7%	spr uncert

Method:
Measured absorbed dose with graphite calorimeter and measured ionization in cavity at same place in phantom. Made 0.15% point of measurement correction to ion chamber where BIPM makes 0.5% for same effect(Kp). Include 0.2% uncert for this correction plus 0.7% for spr.

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)^{\rm gr}_{\rm air} = \frac{D}{(I/m)K_{\rm p}}$$

Used ^{137}Cs. Gap effects could influence result.

Weights

for $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$: 19%
for $\left(\frac{W}{e}\right)_{\rm air}$: 6%

6.9 Paper 12

J.P. Guiho and J.P. Simoen, **Détermination Expérimentale de L'énergie Moyenne Nécéssaire á la Production d'une Paire d'ions dans l'Air**, Int'l J Appl. Rad. Isot. **26** (1975) 714 – 719.

Table 12:

	$\left(\frac{W}{e}\right)_{\rm air}$ (J/C, eV/ip)	uncertainty		comments
		J/C	%	
reported	33.96	0.34	1.0%	clearly 3σ
				s = 1.0035
ICRU	33.96			
B&PR	34.02	0.10	0.29%	s = 1.002
		0.14	0.41%	
NRC	33.82	0.11	0.34%	add 0.2% uncert,0.6% change X
		0.26	0.75%	0.7% spr

Method:
Used X from many chambers and measured absorbed dose in small graphite calorimeter. Made various corrections for geometry and back scatter.

$$\left(\frac{W}{e}\right) X = D \left(\frac{\overline{\mu_{\rm en}}}{\rho}\right)^{\rm air}_{\rm gr} \frac{1}{t_c(x)}$$

$$\left(\frac{W}{e}\right) \left(\frac{\overline{L}}{\rho}\right)^{\rm gr}_{\rm air} = \frac{D}{(Q/m)Kt_c(x)}$$

Correction t is 2% but little discussion (0.1% 1σ). Add arbitrary 0.2% uncertainty. Note also that changes in $K_{\rm wall}$ and $K_{\rm pn}$ will affect this value. Assume X changes by average in Bielajew and Rogers 1992, i.e. 0.6%, then $\left(\frac{W}{e}\right)_{\rm air}$ decreases by 0.6% and this has been done.

Weights

for $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$: 13%
for $\left(\frac{W}{e}\right)_{\rm air}$: 4%

6.10 Paper 13

M.T. Niatel, A.M. Perroche-Roux and M. Boutillon, **Two determinations of W for electrons in dry air**, Phys. Med. Biol. **30** (1985) 67 – 75.

Table 13:

	$\left(\frac{W}{e}\right)_{\text{air}}$ (J/C, eV/ip)	uncertainty J/C	uncertainty %	comments
reported	33.96	0.04	0.12%	
		0.11	0.32%	
ICRU	33.96			
B&PR	33.96	0.04	0.12%	
		0.11	0.32%	
NRC	33.96	0.08	0.23%	0.2% on K_p
		0.25	0.74%	0.7% spr

Method:
Many graphite calorimeters vs ionization in graphite with a calculated perturbation correction of 0.5% (where paper 11 uses 0.15% for same correction). Added 0.2% arbitrary uncertainty.

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)^{\text{gr}}_{\text{air}} = \frac{D}{(I/m)K_{\text{p}}}$$

Gap effect and uniformity corrections would apply here, but tend to cancel out.

Weights

for $\left(\frac{W}{e}\right)_{\text{air}} s_{\text{gr,air}}$: 25%
for $\left(\frac{W}{e}\right)_{\text{air}}$: 7%

6.11 Paper 14

R. Kunze and O. Hecker, **Bestimmung des mittleren Energieaufwandes W(luft) zur Bildung eines Ionenpaares in Luft fur ^{60}Co–γ–Strahlung**, Isotopenpraxis **16** (1980) 325 – 327.

Table 14:

	$\left(\frac{W}{e}\right)_{\rm air}$ (J/C, eV/ip)	uncertainty		comments
		J/C	%	
reported	33.87	0.34	1.0%	2σ, s=1.009(5)
B&PR	34.27	0.15	0.44%	s=1.002
		0.18	0.53%	
NRC	34.27	0.16	0.47%	uncert 0.2% $P_{\rm repl}$
		0.27	0.81%	0.7% spr

Method:
Based on calorimeter and ionization in air cavity in phantom.

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)^{\rm gr}_{\rm air} = \frac{D}{(I/m)K_{\rm p}}$$

Not clear if cavity perturbation included (paper in German which I don't read).

Weights

for $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$: 6%
for $\left(\frac{W}{e}\right)_{\rm air}$: 2%

6.12 Paper 15

M.T. Niatel, A.M. Perroche-Roux and M. Boutillon, **Two determinations of W for electrons in dry air**, Phys. Med. Biol. **30** (1985) 67 – 75.

Table 15:

	$\left(\frac{W}{e}\right)_{\rm air}$ (J/C, eV/ip)	uncertainty J/C	uncertainty %	comments
reported	33.81	0.12	0.35%	
		0.16	0.47%	
ICRU	33.81			
NRC	33.73	0.17	0.5%	uncert from muen,X adjust
		0.29	0.86%	muen and spr

Method:
Use known exposure rate at a point from cavity ionization chamber and use known source activity to deduce energy fluence times mass-energy absorption coefficient for graphite(air cancels out).

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)^{\rm gr}_{\rm air} = AE_\gamma\left(\frac{\overline{\mu_{\rm en}}}{\rho}\right)_{\rm gr}\frac{m_{\rm air}}{4\pi r^2 I}\frac{K_s}{K_X}$$

Whole uncertainty is mass-energy absorption coefficient and Hubbell gives 1.0% with no stated confidence, but can assume it is like ICRU 37, i.e. 90% (based on phone call). This increases the uncertainty from 0.35 to 0.5%.

Used NRC changes to BIPM X (0.25% increase) leads to decrease in $\left(\frac{W}{e}\right)_{\rm air}$.

Weights

for $\left(\frac{W}{e}\right)_{\rm air} s_{\rm gr,air}$: 5%
for $\left(\frac{W}{e}\right)_{\rm air}$: 2%

7 Appendix B: Weighted Averaging With Correlations

If there are n independent estimates of $w(i)$ with total uncertainties (1σ) on each of $err(i)$, then the weighted least squares value of $\overline{w}$ is:

$$\overline{w} = \frac{\sum \frac{w(i)}{err(i)^2}}{\sum \frac{1}{err(i)^2}} \tag{5}$$

and assuming the uncertainties are correct, the internal uncertainty is:

$$err_{in}\overline{w} = \sqrt{\frac{1}{\sum \frac{1}{err(i)^2}}}. \tag{6}$$

However, if the fit is very poor (*i.e.* large scatter and χ^2 per degree of freedom) then a more realistic estimate of the 68% confidence interval (called the external estimate) is:

$$err_{ex}\overline{w} = err_{in}\overline{w}\ t(n-1)\sqrt{\chi^2/(n-1)}, \tag{7}$$

where $t(n{-}1)$ is the student's t distribution with n-1 degrees of freedom and $\chi^2 = \sum \left(\frac{w(i)-\overline{w}}{err(i)}\right)^2$. As a rule, I use the larger of the internal or external uncertainty estimates in any given case.

If exclusive subgroups of the individual values of w have been determined using a single common multiplicative factor (*e.g.* using $1/\mathrm{s}_{\mathrm{gr,air}}$) and the other part of the determinations are independent, one can proceed as follows. In this case let $errw(i)$ be the uncertainties in the uncorrelated component and $errc$ the percentage uncertainty in the common factor (*e.g.* 0.6% on $1/\mathrm{s}_{\mathrm{gr,air}}$). First determine the weighted average of each subgroup and the uncertainty from the independent components using the equations above for $err_{in}\overline{w}$ or $err_{ex}\overline{w}$. The overall uncertainty in $\overline{w}$ for this group is then determined using the standard rule for the uncertainty on a product (*viz.* $\overline{w}\sqrt{\left(\frac{err_{in}\overline{w}}{\overline{w}}\right)^2 + \left(\frac{errc}{100.}\right)^2}$ in this case). Using these uncertainties for each independent subgroup, the overall uncertainty can be determined by a second application of the formulae above for $err_{in}\overline{w}$ and $err_{ex}\overline{w}$.

Under the restrictions stated above, this is a rigorous procedure and has the advantage of taking into account the consistency of the data (I use the larger of $err_{in}\overline{w}$ and $err_{ex}\overline{w}$ for the first step and $err_{in}\overline{w}$ for the average on the groups since we have assured a reasonable estimate of the uncertainties already). However this procedure does not completely handle the present situation where some estimates are correlated in more than one way (stopping-power ratio, mass energy absorption coefficients and measured X, in papers 7 and 15). These papers have a relatively small weight and thus this oversight is not critical.

This raises the issue of correlations not covered in the earlier analysis, *viz.* between papers 1 and 2 regarding the energy output; between papers 6, 7, 12, and 15 regarding the measurement of X (in particular the A_{wall} and point of measurement corrections) and papers 9, 10, 11, 13 and 14 regarding the cavity perturbation factor. Considering these correlations can only increase the overall uncertainty in $\left(\frac{W}{e}\right)_{\text{air}}$.

References

[1] D.W.O. Rogers, *Fundamentals of High Energy X-ray and Electron Dosimetry Protocols*, in “Advances in Radiation Oncology Physics” ed J. Purdy, Medical Physics Monograph 19 (AAPM, New York) (1992) 181 – 223.

[2] M. Boutillon, *Perturbation correction for the ionometric determination of absorbed dose in a graphite phantom for ^{60}Co gamma rays*, Phys. Med. Biol. **28** (1983) 375 – 388.

[3] M. Boutillon and A.-M. Perroche, *Ionometric determination of absorbed dose in water for cobalt-60 gamma rays*, Phys. Med. Biol. **38** (1993) 439 – 454.

[4] H. Svensson and A. Brahme, *Recent Advances in Electron and Photon Dosimetry*, Ch 3 in “Radiation Dosimetry” ed by C.G. Orton (Plenum Publishing) (1986) 87 – 170.

[5] C. Malamut, D.W.O. Rogers and A.F. Bielajew, *Calculation of water/air stopping-power ratios using EGS4 with explicit treatment of electron - positron differences*, Medical Physics **18** (1991) 1222 – 1228.

[6] P. Andreo, *Depth-dose and stopping-power data for monoenergetic electron beams*, Nucl. Instr. Meth. **51** (1990) 107 – 121.

[7] A. Kosunen and D.W.O. Rogers, *Beam Quality Specification for Photon Beam Dosimetry*, in press Med. Phys. **20**(#4) (1993).

[8] D.W.O. Rogers, *The role of Monte Carlo simulation of electron transport in radiation dosimetry*, Int’l J of Appl. Radiation and Isotopes, **42** (1991) 965 – 974.

[9] P. Andreo and A. Fransson, *Stopping-power ratios and their uncertainties for clinical electron beam dosimetry*, Phys. Med. Biol. **34** (1989) 1847 – 1861.

[10] ICRU, *Report 37, Stopping Powers for Electrons and Positrons*, (ICRU, Washington D.C.) (1984).

[11] H. Bischel and T. Hiraoka, *Energy loss of 70 MeV protons in elements*, Nucl. Inst. Meth. **B66** (1992) 345 – 351.

[12] J. Mizia and A.F. Bielajew, *The density effect on electron stopping powers in condensed, granular materials*, NRC Report PIRS-0322 (1992) 1 – 10.

[13] M. Boutillon and A.M. Perroche-Roux, *Re-evaluation of the W value for electrons in dry air*, Phys. Med. Biol. **32** (1987) 213 – 219.

[14] D.W.O. Rogers, *Analytic and Graphical Methods for Assigning Errors to Parameters in Non-Linear Least Squares Fitting*, Nuclear Instruments and Methods **127** (1975) 253 – 260.

[15] Z. Bay, W.B. Mann, H.H. Seliger and H.O. Wyckoff, *Absolute Measurement of W_{air} for sulfur-35 Beta Rays*, Rad’n. Res. **7** (1957) 558 – 569.

[16] W. Gross, C. Wingate and G. Failla, *Average Energy Lost by Sulfur-35 Beta Rays per Ion Pair Produced in Air*, Rad'n Res. **7** (1957) 570 – 580.

[17] W.P. Jesse, *Absolute Energy to Produce an Ion Pair in Various Gases by Beta Particles from S^{35}*, Phys. Rev. **109** (1958) 2002 – 2004.

[18] W.P. Jesse and J. Sadaukis, *Absolute Energy to Produce an Ion Pair by Beta Particles From S^{35}*, Phys. Rev. **107** (1957) 766 – 771.

[19] I.T. Myers, W.H. LeBlanc, D.M. Fleming and H.O. Wyckoff, *An Adiabatic Calorimeter for High Precision Source Standardization*, Rad'n Res. **14** (1961) 488 – 489 (abs).

[20] I.T. Myers, W.H. Le Blanc, D.M. Fleming and H.O. Wyckoff, *An Adiabatic Calorimeter for High Precision Source Standardization and Determination of W(air)*, Report HW-SA-2165-US Dept Commerce (1961) 1 – 15.

[21] T.P. Loftus and J.T. Weaver, *Standardization of ^{60}Co and $137Cs$ Gamma-Ray Beams in Terms of Exposure*, J Res of Nat Bur Stand. A **78A** (1974) 465 – 476.

[22] A.F. Bielajew and D.W.O. Rogers, *Implications of new correction factors on primary air kerma standards in ^{60}Co beams*, Phys. Med. Biol. **37** (1992) 1283 – 1291.

[23] M.J. Berger, *Monte Carlo Calculation of the penetration and diffusion of fast charged particles*, Methods in Comput. Phys. **1** (1963) 135 – 215.

[24] B. Petree and P. Lamperti, *A Comparison of Absorbed Dose Determinations in Graphite by Cavity Ionization Measurements and by Calorimetry*, J of Res. of NBS, Vol **71C** (1967) 19 – 27.

[25] B.A. Engelke and K. Hohlfeld, *A calorimeter as a standard device to measure absorbed doses and the determination of the mean energy absorbed to generate an ion-pair in air (translated from German)*, PTB Mitteilungen **71** (1971) 336 – 342.

[26] J.P. Guiho and J.P. Simoen, *Détermination Expérimentale de L'énergie Moyenne Nécéssaire á la Production d'une Paire d'ions dans l'Air*, Int'l J Appl. Rad. Isot. **26** (1975) 714 – 719.

[27] M.T. Niatel, A.M. Perroche-Roux and M. Boutillon, *Two determinations of W for electrons in dry air*, Phys. Med. Biol. **30** (1985) 67 – 75.

[28] M. Boutillon, *Revision of the results of international comparisons of absorbed dose in graphite in a ^{60}Co beam*, BIPM Report BIPM–90/4 (1990).

[29] R. Kunze and O. Hecker, *Bestimmung des mittleren Energieaufwandes W(luft) zur Bildung eines Ionenpaares in Luft fur ^{60}Co–γ–Strahlung*, Isotopenpraxis **16** (1980) 325 – 327.

Paper 1

$$E_{out} = \left(\frac{W}{e}\right) I$$

Paper 2

$$E_{out} = \left(\frac{W}{e}\right) N \left(\frac{\overline{L}}{\rho}\right)^{\text{water}}_{\text{air}}$$

Paper 3

$$AE_{\text{ave}} = \left(\frac{W}{e}\right) I$$

Paper 6

$$X\left(\frac{W}{e}\right) = \Psi \left(\frac{\overline{\mu_{\text{en}}}}{\rho}\right)_{\text{air}}$$

Paper 7

$$X\left(\frac{W}{e}\right) = \Psi \left(\frac{\overline{\mu_{\text{en}}}}{\rho}\right)_{\text{air}}$$

Paper 9

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)^{\text{gr}}_{\text{air}} = \frac{D}{I/m}$$

Paper 10

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)^{\text{gr}}_{\text{air}} = \frac{D}{I/m}$$

Paper 11

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)^{\text{gr}}_{\text{air}} = \frac{D}{(I/m)K_{\text{p}}}$$

Paper 12

$$\left(\frac{W}{e}\right) X = D \left(\frac{\overline{\mu_{\text{en}}}}{\rho}\right)^{\text{air}}_{\text{gr}} \frac{1}{t_c(x)}$$

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)^{\text{gr}}_{\text{air}} = \frac{D}{(Q/m)Kt_c(x)}$$

Paper 13

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)^{\text{gr}}_{\text{air}} = \frac{D}{(I/m)K_{\text{p}}}$$

Paper 14

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)^{\text{gr}}_{\text{air}} = \frac{D}{(I/m)K_{\text{p}}}$$

Paper 15

$$\left(\frac{W}{e}\right)\left(\frac{\overline{L}}{\rho}\right)^{\text{gr}}_{\text{air}} = AE_{\gamma} \left(\frac{\overline{\mu_{\text{en}}}}{\rho}\right)_{\text{gr}} \frac{m_{\text{air}}}{4\pi r^2 I} \frac{K_s}{K_X}$$