New ICRU Recommendations on Key Data for Ionizing Radiation Dosimetry

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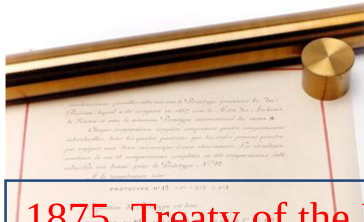
NIST

CIRMS 2016

International Commission on Radiation Units & Measurements

International Harmonization in Ionizing Radiation



1875, Treaty of the Meter
Establishes the CIPM (International Committee on Weights and Measures) and the laboratory BIPM (International Bureau of Weights and Measures)

1895, Roentgen discovers x rays
1898, Curie discovers radium

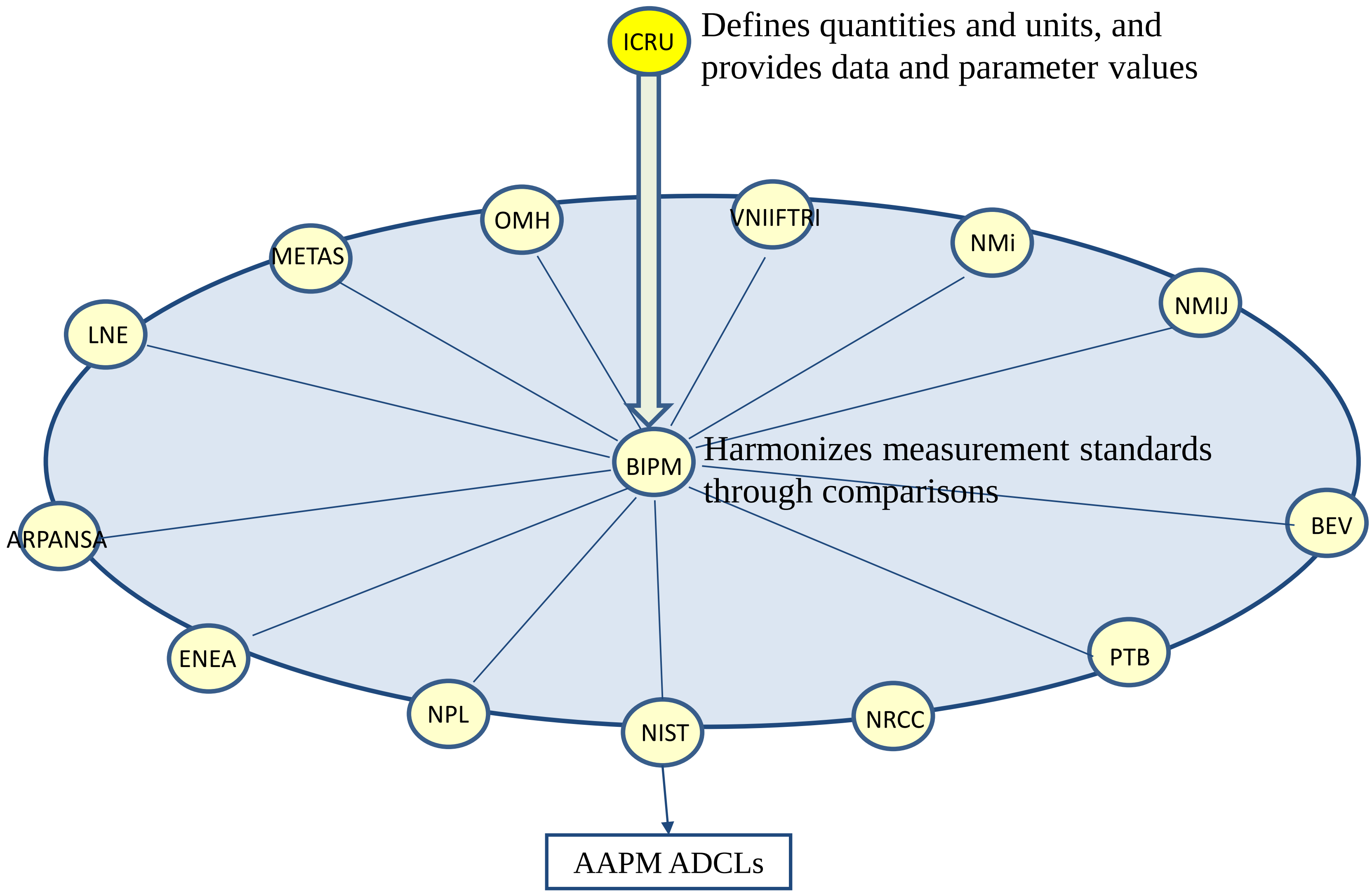
1925, ICRU is established

From recommendations of the ICRU

1960, CCRI (Consultative Committee on Ionizing Radiation) is established

CCRI(I), Section I: x- and gamma-rays and charged particles
CCRI(II), Section II: measurement of radionuclides
CCRI(III), Section III: neutron measurements

Two-Part Harmony in Ionizing Radiation



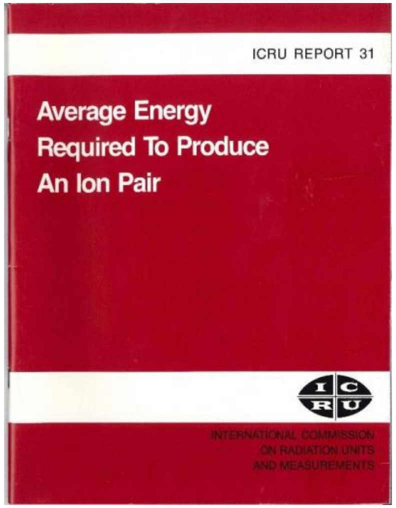
Reasons for This Work

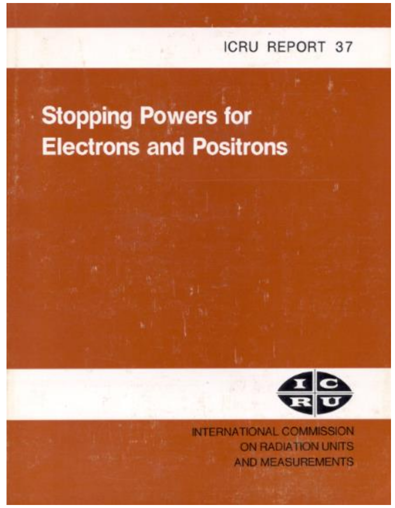
Work instituted at the request of the Consultative Committee on Ionizing Radiation, CCRI(I), primarily to address issues about parameters that affect air-kerma (or ionometric) standards.

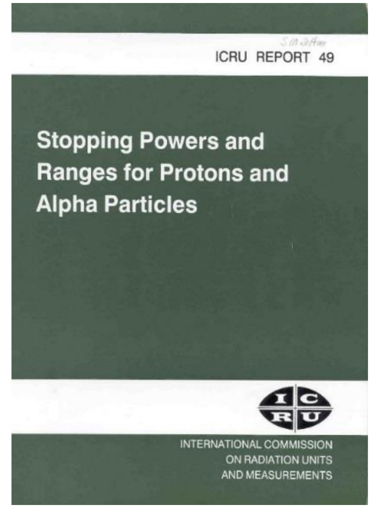
Up till now, consensus values of parameters (that will soon be explained):

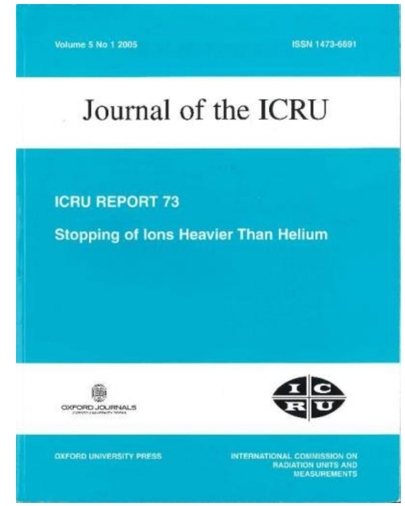
- For electrons produced by x and gamma rays, mean energy per ion pair formed in air, $W/\mathrm{e} = (33.97 \pm 0.05)$ J/C
- Use values of graphite-to-air electron-stopping-power ratios that are calculated based on the recommendations of ICRU Report 37 (1984)
- Noted a 1992 report of measurement result for I_{graphite} value that would change stopping-power ratios, and international standards for air kerma, by more than 1 %
- One actually measures the product of W/e and the graphite-to-air stopping-power ratio, so the two quantities are not independent

Effort Would Include Advancing Relevant Past ICRU Work
(among others)

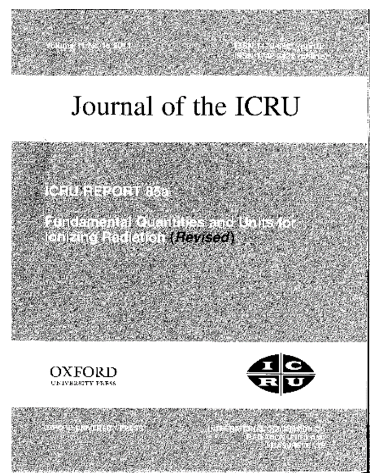








and be consistent with



ICRU Report
KEY DATA FOR IONIZING-RADIATION DOSIMETRY: MEASUREMENT STANDARDS AND APPLICATIONS

Report Committee

Stephen Seltzer (Co-Chairman), National Institute of Standards and Technology
Jose Fernandez-Varea (Co-Chairman), University of Barcelona
Pedro Andreo, Karolinska University Hospital
Paul Bergstrom, National Institute of Standards and Technology
David Burns, Bureau International des Poids et Mesures
Ines Krajcar-Bronic, Rudjer Bošković Institute
Carl Ross, National Research Council
Francesc Salvat, University of Barcelona

ICRU Sponsors

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Herwig Paretzke, Helmholtz Zentrum

Consultants

H. Bichsel, University of Washington
D. Emfietzoglou, University of Ioannina Medical School
H. Paul (deceased), Institute for Experimental Physics, Johannes-Kepler Universität

Main Issues Considered by the Report Committee

Charged Particles: electrons, positrons, protons, alpha particles, carbon ions

- Mean excitation energies, I: air, graphite, liquid water
- Density effect in graphite
- Mean energy to produce an ion pair in air, W_{air}

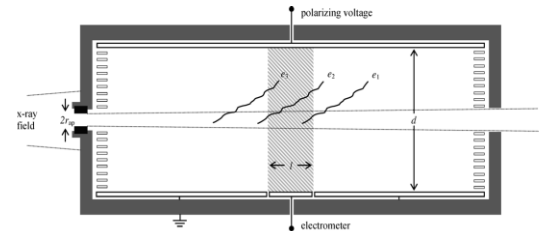
Photons:

- Photon cross sections: air, graphite, liquid water
- Photon attenuation, energy-transfer, and energy-absorption coefficients

Why Do We Care?
Illustrative Measurement Equations

To realize x-ray air kerma with a free-air chamber

$$K_{\text{air}} = (W_{\text{air}}/\text{e})\,\frac{q_{\text{net}}}{m_{\text{air}}(1-\bar{g}_{\text{air}})}\prod_i k_i$$

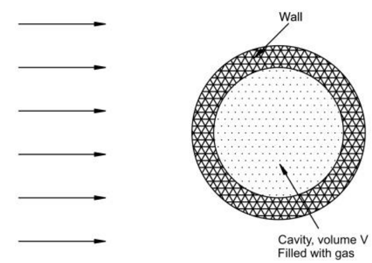


To realize gamma-ray air kerma with a graphite-walled Bragg-Gray cavity chamber

$$K_{\text{air}} = \left(W_{\text{air}}/\text{e}\right)\frac{q_{\text{net}}}{m_{air}(1-\bar{g}_{\text{air}})}\,s_{\text{g,air}}\,(\mu_{\text{en}}/\rho)_{\text{air,g}}\prod_i k_i$$

with notation

$$s_{\text{g,air}} = \frac{\overline{\left(S_{\text{el}}/\rho\right)}_{\text{graphite}}}{\overline{\left(S_{\text{el}}/\rho\right)}_{\text{air}}}$$



and

$$\left(\mu_{\text{en}}/\rho\right)_{\text{air,g}} = \frac{\overline{\left(\mu_{\text{en}}/\rho\right)}_{\text{air}}}{\overline{\left(\mu_{\text{en}}/\rho\right)}_{\text{graphite}}}$$

Illustrative Measurement Equations

To realize x-ray air kerma with a free-air chamber

$$K_{\mathrm{air}} = (W_{\mathrm{air}}/\mathrm{e}) \frac{q_{\mathrm{net}}}{m_{\mathrm{air}}(1-\bar{g}_{\mathrm{air}})} \prod_i k_i$$

Need value for electrons

Need brems production cross sections

To realize gamma-ray air kerma with a graphite-walled Bragg-Gray cavity chamber

$$K_{\mathrm{air}} = (W_{\mathrm{air}}/\mathrm{e}) \frac{q_{\mathrm{net}}}{m_{air}(1-\bar{g}_{\mathrm{air}})} s_{\mathrm{g,air}} (\mu_{\mathrm{en}}/\rho)_{\mathrm{air,g}} \prod_i k_i$$

where

$$s_{\mathrm{g,air}} = \frac{\overline{(S_{\mathrm{el}}/\rho)}_{\mathrm{graphite}}}{\overline{(S_{\mathrm{el}}/\rho)}_{\mathrm{air}}}$$

Need *I* value and density effect

and

$$(\mu_{\mathrm{en}}/\rho)_{\mathrm{air,g}} = \frac{\overline{(\mu_{\mathrm{en}}/\rho)}_{\mathrm{air}}}{\overline{(\mu_{\mathrm{en}}/\rho)}_{\mathrm{graphite}}}$$

Need best values and uncertainty of ratio

Elaboration for Measurement Equations

Photons:

$$\frac{\overline{(\mu_{\text{en}}/\rho)}_{\text{air}}}{\overline{(\mu_{\text{en}}/\rho)}_{\text{graphite}}} = \frac{\int \Phi_E E \left(\frac{\mu_{\text{en}}(E)}{\rho}\right)_{\text{air}} \mathrm{d}E}{\int \Phi_E E \left(\frac{\mu_{\text{en}}(E)}{\rho}\right)_{\text{graphite}} \mathrm{d}E}$$

incident photon fluence

Electrons:

$$\frac{\overline{(S/\rho)}_{\text{graphite}}}{\overline{(S/\rho)}_{\text{air}}} = \frac{\int_{\Delta}^{T_{\max}} \Phi_T^{\text{air}} \left(\frac{S_\Delta^-(T)}{\rho}\right)_{\text{graphite}} \mathrm{d}T + \Phi_T^{\text{air}}(\Delta)\left(\frac{S_{\text{el}}^-(\Delta)}{\rho}\right)_{\text{graphite}} \Delta}{\int_{\Delta}^{T_{\max}} \Phi_T^{\text{air}} \left(\frac{S_\Delta^-(T)}{\rho}\right)_{\text{air}} \mathrm{d}T + \Phi_T^{\text{air}}(\Delta)\left(\frac{S_{\text{el}}^-(\Delta)}{\rho}\right)_{\text{air}} \Delta}$$

electron fluence in cavity

mass electronic stopping power

where the restricted electronic stopping power is

$$\frac{1}{\rho} S_\Delta^{\pm}(T) = \frac{2\pi r_{\text{e}}^2 m_{\text{e}} c^2}{\beta^2} \frac{Z}{uA} \left(\ln\left[(T/I)^2 (1+\tau/2) \right] - \delta - H^{\pm}(\tau) \right)$$

mean excitation energy

density-effect correction

Key Data for Charged Particles

- W_{air} mean energy expended in dry air per ion pair formed
- I_{air}
- $I_{graphite}$
- I_{water}

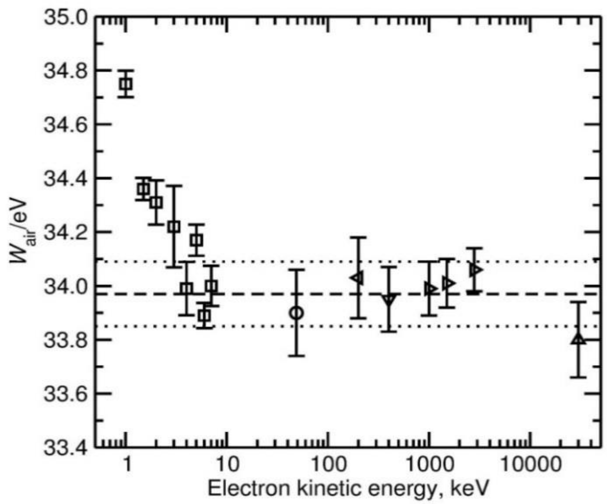
mean excitation energy of the medium to calculate the electronic stopping power of charged particles

- δ density-effect correction to the electronic stopping power of charged particles
- g_{air} the fraction, averaged over the distribution of the air kerma with respect to the electron energy, of the kinetic energy of electrons liberated by the photons that is lost in radiative processes (mainly bremsstrahlung) in dry air

Background: Mean Energy to Produce an Ion Pair in Air

- Since the publication of ICRU Report 31 (1979), there have been a number of reports on the determination of W_{air} for electrons and on w_{air} in nitrogen and air for protons.

- ICRU Report 73, based on an analysis of Jones (2006), recommends a value of w_{air}/e for proton therapy of (34.2 ± 0.1) J C^{-1}. The Key Data Report Committee accepts this value and focuses mainly on W_{air} for electrons.



- A collection of precision experiments measures the product $W_{air} \cdot s_{graphite,air}$, so the recommended values of W_{air}, $I_{graphite}$, and $\rho_{graphite}$ are intertwined.

Background: Mean Excitation Energies

The mean excitation energy *I* is a key and non-trivial parameter in Bethe stopping-power theory, used in charged-particle transport and dosimetry.

- ICRU Report 37 (1984) on e^- and e^+ stopping powers recommended $I_{graphite}$= (78.0 ± 4.3) eV, I_{air} = (85.7 ± 1.2) eV, and I_{water} = (75.0 ± 1.8) eV. These values retained in ICRU Report 49 (1993) for the calculation of p and α stopping powers.

- Bichsel and Hiraoka (1992), analyzing energy loss of 70 MeV protons in 21 (mostly elemental) materials relative to Al, reported $I_{graphite}$ = (86.9 ± 1.2) eV, and I_{water} = (79.7 ± 0.5) eV. Recent analyses of the dielectric-response function for liquid water recommend values of I_{water} larger than 75 eV.

- Considered by itself, such a change in the mean excitation energy for graphite can have a large effect in national air-kerma standards, ≈1.3 % for ^{60}Co, ≈1.5 % for ^{137}Cs, and ≈1.5 % for ^{192}Ir.

- As water is the universal dosimetry reference material, I_{water} is also considered.

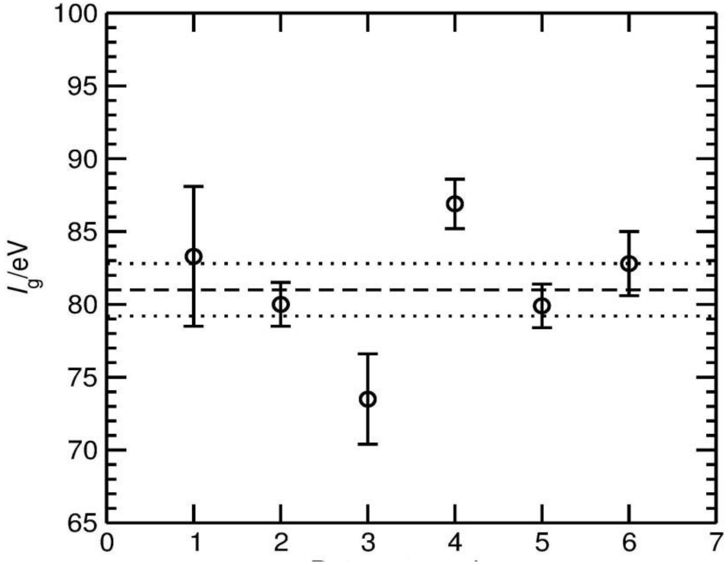
- ICRU Report 73 considered stopping of ions heavier than He, <u>but not in the context of Bethe theory</u>.

Mean Excitation Energies

air

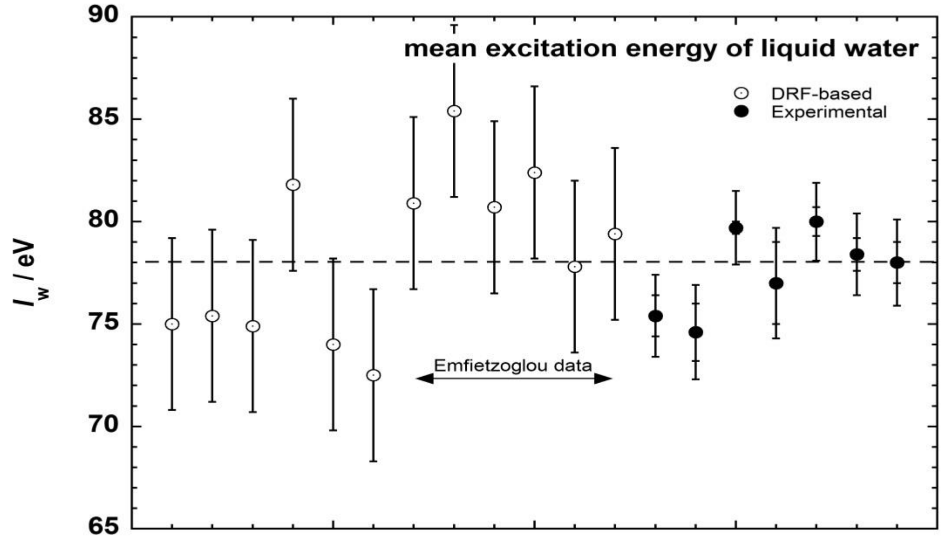
data from 1955 to 2006

Constituent	Fraction by weight	<Z/A>	Recommended	
			I/eV	u_c/eV
N_2	0.755267	0.499761	82.3	1.22
O_2	0.231450	0.500019	95.2	1.0
Ar	0.012827	0.450586	187	3
CO_2	0.000456	0.499889	86	1.3
Dry air	1	0.499190	85.7	1.2



graphite

data from 1951 to 2007



water

data from 1952 to 2009

Background: Density Effect

- Graphite is not a simple homogeneous material. ICRU Report 37 (1984) recommended the use of the bulk density in the calculation of the density effect, but considers also treating inhomogeneous materials as a mixture.

- Applied to the case of graphite, a mixture-with-air approach gives values of the electronic stopping power that are the same to four significant figures as those for pure graphite with the crystallite density $\rho_{\text{graphite}} = 2.265\ \text{g/cm}^3$. This is consistent with the suggestion of MacPherson (1998) who found better agreement with the measured energy loss of 6 MeV to 28 MeV electrons in graphite when they use a crystallite density of 2.26 g/cm^3 rather than the bulk density ($\approx$ 1.7 g/cm^3) for the calculation of the density-effect correction.

- The use of the crystallite density rather than the bulk density changes the graphite-to-air stopping-power ratio associated with graphite-wall air-ionization cavity chambers by $\approx$ 0.2 % for ^{60}Co, $\approx$ 0.1 % for ^{137}Cs, and $\approx$0.06 % for ^{192}Ir.

Background: g_{air}

- g_{air} is an average over the bremsstrahlung yield Y of secondary electrons slowing down in air

- Y is evaluated as $Y(T_0) = \int_0^{T_0} \frac{S_{rad}(T)}{S_{el}(T) + S_{rad}(T)} \mathrm{d}T$

- S_{rad} is the radiative stopping power, which depends on bremsstrahlung-production cross sections

- bremsstrahlung-production cross sections adopted from work of Seltzer and Berger (1985), which is slightly different from that used in ICRU Report 37 (1984)

- final effect on g_{air} is of order 0.5 % or less and g_{air} itself is about 0.0033 for ^{60}Co air kerma, <u>so effect on 1- g_{air} is negligible</u>

Summary of Recommendations
Charged Particles

	Previous	This Report	Standard uncertainty	Relative standard uncertainty (%)	Relative change (%)	Comments
W_{air} for electrons	33.97 eV	33.97 eV	0.12 eV	0.35	**0**	Asymptotic value
W_{air} for protons	34.23 eV	34.44 eV	0.14 eV	0.4	**0.6**	Asymptotic value
W_{air} for C ions	34.50 eV	34.71 eV	0.52 eV	1.5	**0.6**	Asymptotic value
h_w (4 °C)	0	0		0.15	**0**	Low-LET radiations
$G(Fe^{3+})$		1.62 μmol J^{-1}	0.008 μmol J^{-1}	~0.5		High energy electrons
I_{air}	85.7 eV	85.7 eV	1.2 eV	1.40	**0**	
I_g	78 eV	81 eV	1.8 eV	2.22	**3.8**	graphite ρ = 2.265 g cm^{-3}
I_w	75 eV	78 eV	2 eV	2.56	**4.0**	

The analysis of Burns (2012) results in the best estimate of $W_{air}\, s_{g,air}$ = 33.72 eV for ^{60}Co radiation, determined with a relative standard uncertainty of 0.08 %. Adoption of this result would reduce the air-kerma determination for ^{60}Co graphite-cavity standards by about 0.7 %, due to the change in $s_{g,air}$.

Recommendations in Context

Density Effect

For graphite use the crystallite density, $\rho_{graphite}$ = 2.265 g/cm^3

Mean Excitation Energies

Air

- I_{air} = (85.7 ± 1.2) eV. I_{air} unchanged but with smaller uncertainty.

Graphite

Reported *I* values range from about 71 eV to 87 eV. Recommendation by the Committee is

- $I_{graphite}$ = (81.0 ± 1.8) eV. Previous was (78 ± ~4) eV

Water

Reported *I* values range from about 75 eV to 82 eV. Recommendation by the Committee is

- I_{water} = (78 ± 2) eV. Previous was (75 ± 2) eV

Mean Energy to Produce an Ion Pair in Air by Electrons

- W_{air} = (33.97 ± 0.12) eV. No change in value, but now has a larger uncertainty

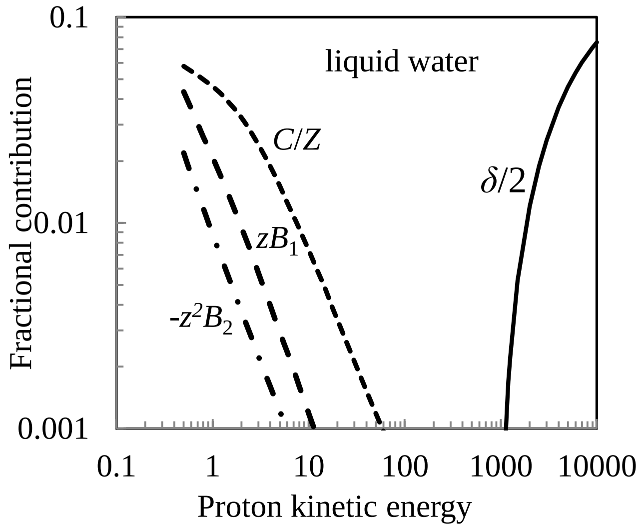
Bethe Theory for Heavy Charged Particles

Electronic (collision) stopping power:

$$\frac{1}{\rho}S_{\mathrm{el}} = \frac{4\pi r_e^2 m_e c^2}{\beta^2}\frac{Z}{uA}z^2 B(\beta)$$

where stopping number is

$$B(\beta) = \ln\left(\frac{2m_e c^2\beta^2}{\left(1-\beta^2\right)I}\right) - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} + zB_1 + z^2 B_2$$



shell correction

Barkas correction

Bloch correction

Sample (Abridged) Stopping-Power/Range Tables

Electrons in liquid water, I = 78 eV

fractional change per
fractional change in I

T	S_{el}/ρ	S_{rad}/ρ	S_{tot}/ρ	r_0/ρ	Y	δ	$\partial(\log\ )/\partial(\log I)$		
MeV	MeV cm^2 g^{-1}			g cm^{-2}			S_{el}/ρ	r_0/ρ	Y
0.001	1.181E+02	2.830E-03	1.181E+02	4.235E-06	1.199E-05	0.000E+00	-0.370	0.370	0.370
0.002	7.436E+01	3.307E-03	7.436E+01	1.524E-05	2.318E-05	0.000E+00	-0.295	0.336	0.334
0.005	3.806E+01	3.737E-03	3.807E+01	7.536E-05	5.253E-05	0.000E+00	-0.232	0.270	0.267
0.010	2.239E+01	3.890E-03	2.239E+01	2.537E-04	9.476E-05	0.000E+00	-0.200	0.229	0.227
0.020	1.308E+01	3.939E-03	1.309E+01	8.632E-04	1.670E-04	0.000E+00	-0.176	0.198	0.197
0.050	6.564E+00	4.011E-03	6.568E+00	4.348E-03	3.442E-04	0.000E+00	-0.152	0.168	0.168
0.100	4.093E+00	4.211E-03	4.097E+00	1.439E-02	5.851E-04	0.000E+00	-0.139	0.151	0.151
0.200	2.779E+00	4.771E-03	2.784E+00	4.512E-02	9.831E-04	0.000E+00	-0.127	0.138	0.137
0.500	2.025E+00	7.228E-03	2.032E+00	1.774E-01	1.976E-03	0.000E+00	-0.113	0.123	0.122
1.000	1.845E+00	1.276E-02	1.858E+00	4.384E-01	3.577E-03	2.086E-01	-0.061	0.097	0.090
2.000	1.821E+00	2.666E-02	1.848E+00	9.811E-01	7.071E-03	7.703E-01	-0.036	0.068	0.055
5.000	1.891E+00	7.922E-02	1.970E+00	2.554E+00	1.910E-02	1.906E+00	-0.022	0.042	0.029
10.000	1.967E+00	1.816E-01	2.148E+00	4.980E+00	4.077E-02	2.928E+00	-0.018	0.031	0.021
20.000	2.045E+00	4.079E-01	2.453E+00	9.327E+00	8.357E-02	4.039E+00	-0.013	0.022	0.015
50.000	2.139E+00	1.145E+00	3.284E+00	1.985E+01	1.920E-01	5.665E+00	-0.005	0.014	0.007
100.000	2.202E+00	2.437E+00	4.640E+00	3.259E+01	3.190E-01	6.998E+00	-0.001	0.009	0.003
200.000	2.263E+00	5.103E+00	7.366E+00	4.955E+01	4.701E-01	8.367E+00	0.000	0.006	0.001
500.000	2.341E+00	1.323E+01	1.558E+01	7.692E+01	6.620E-01	1.019E+01	0.000	0.004	0.000
1000.000	2.401E+00	2.691E+01	2.931E+01	9.994E+01	7.764E-01	1.158E+01	0.000	0.003	0.000

Sample (Abridged) Stopping-Power/Range Tables

Protons in liquid water, I = 78 eV

fractional change per fractional change in I

T MeV	S_{el}/ρ	S_{nuc}/ρ	S_{tot}/ρ	r_0/ρ g cm^{-2}	Detour factor	$\partial\log/\partial\log(I)$	
	MeV cm^{-2} g^{-1}					(S_{el}/ρ)	r_0/ρ
0.2	6.585E+02	9.016E-01	6.594E+02	2.967E-04	0.9460	-0.081	0.006
0.5	4.065E+02	4.043E-01	4.069E+02	8.945E-04	0.9790	-0.394	0.220
1.0	2.574E+02	2.173E-01	2.577E+02	2.487E-03	0.9905	-0.311	0.298
2.0	1.569E+02	1.157E-01	1.570E+02	7.639E-03	0.9952	-0.256	0.283
5.0	7.842E+01	4.970E-02	7.847E+01	3.656E-02	0.9974	-0.206	0.235
10.0	4.532E+01	2.603E-02	4.535E+01	1.240E-01	0.9980	-0.179	0.203
20.0	2.589E+01	1.356E-02	2.591E+01	4.289E-01	0.9983	-0.159	0.177
50.0	1.238E+01	5.691E-03	1.238E+01	2.240E+00	0.9985	-0.140	0.152
100.0	7.250E+00	2.944E-03	7.253E+00	7.759E+00	0.9987	-0.128	0.138
200.0	4.470E+00	1.522E-03	4.471E+00	2.609E+01	0.9988	-0.119	0.127
500.0	2.731E+00	6.367E-04	2.732E+00	1.176E+02	0.9990	-0.109	0.116
1000.0	2.203E+00	3.300E-04	2.204E+00	3.268E+02	0.9992	-0.096	0.108
2000.0	2.017E+00	1.715E-04	2.017E+00	8.079E+02	0.9994	-0.052	0.084
5000.0	2.029E+00	7.251E-05	2.030E+00	2.302E+03	0.9996	-0.027	0.052
10000.0	2.124E+00	3.788E-05	2.125E+00	4.707E+03	0.9998	-0.019	0.037

Sample (Abridged) Stopping-Power/Range Tables

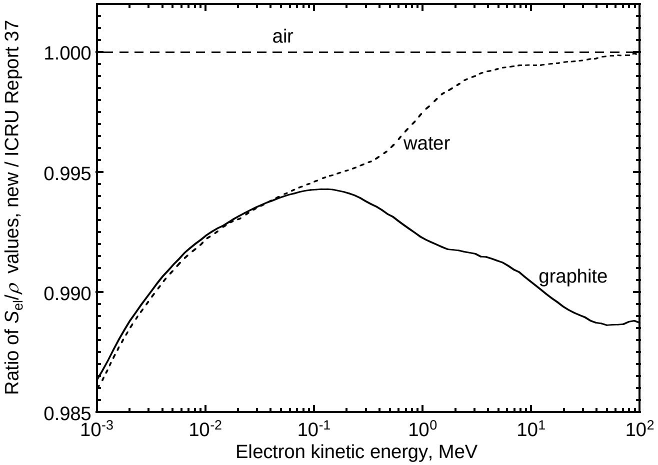
Carbon ions in liquid water, I = 78 eV

fractional change per
fractional change in I

T	S_{el}/ρ	S_{nuc}/ρ	S_{tot}/ρ	r_0/ρ	$\partial(\log\ )/\partial(\log I)$	
MeV		MeV cm^2 g^{-1}		g cm^{-2}	S_{el}/ρ	r_0/ρ
0.5	4.198E+03	1.001E+02	4.298E+03	1.911E-04	0	0
1	6.116E+03	5.808E+01	6.174E+03	2.864E-04	0	0
2	8.139E+03	3.302E+01	8.172E+03	4.238E-04	0	0
5	8.372E+03	1.529E+01	8.387E+03	7.708E-04	0	0
10	6.926E+03	8.428E+00	6.934E+03	1.430E-03	0	0
20	5.284E+03	4.603E+00	5.289E+03	3.100E-03	0	0
50	3.134E+03	2.043E+00	3.136E+03	1.072E-02	-0.179	0.048
100	1.855E+03	1.094E+00	1.856E+03	3.222E-02	-0.188	0.147
200	1.069E+03	5.806E-01	1.070E+03	1.063E-01	-0.165	0.165
500	5.123E+02	2.468E-01	5.126E+02	5.438E-01	-0.143	0.153
1000	2.984E+02	1.271E-01	2.985E+02	1.881E+00	-0.131	0.140
2000	1.813E+02	6.474E-02	1.814E+02	6.369E+00	-0.121	0.129
5000	1.068E+02	2.615E-02	1.068E+02	2.940E+01	-0.110	0.117
10000	8.311E+01	1.312E-02	8.312E+01	8.401E+01	-0.102	0.110

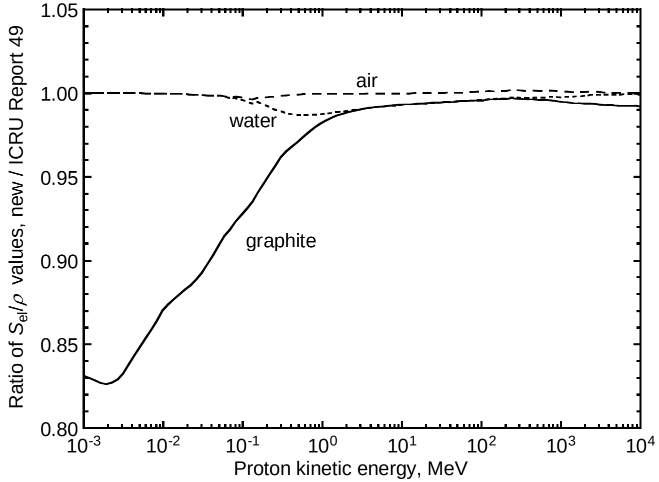
based on empirical results

Changes in Electronic Stopping Powers

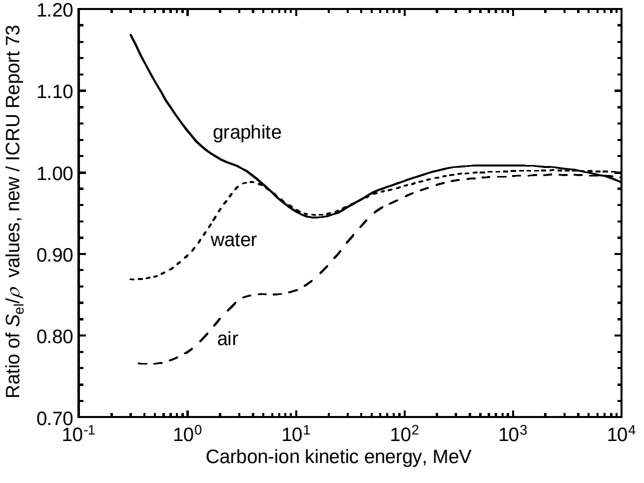


electrons

protons



C ions



Anticipated Impact of Recommendations

Measurement Standards:
The recommended changes for graphite *I* and density would result in a relative decrease of about 0.6 % – 0.7 % in international measurement standards for ^{60}Co, ^{137}Cs, and ^{192}Ir air kerma.

Estimated relative changes (%) in NIST air-kerma standards

^{60}Co	-0.66
^{137}Cs	-0.61
^{192}Ir	-0.59

Particle Therapy:
For therapy energies, the recommended change in I_{water} from 75 eV to 78 eV results in an increase in the csda range of:

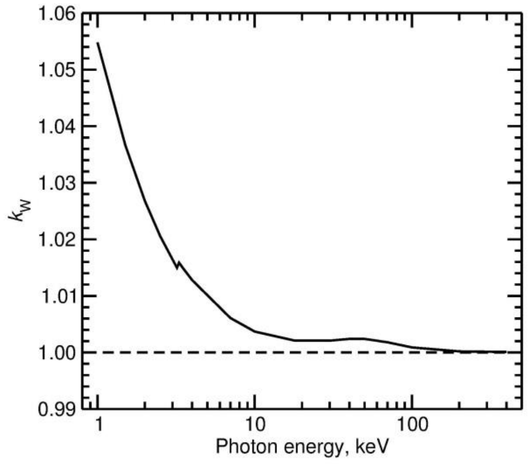
- 0.08 mm for 20 MeV electrons
- 1.3 mm for 200 MeV protons
- 0.9 mm for C ions (300 MeV/u)

Anticipated Impact of Recommendations (cont'd)

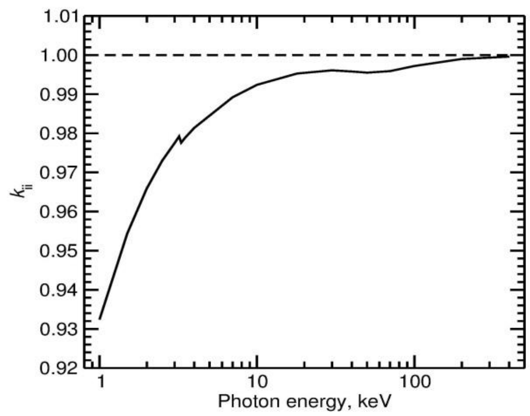
Clinical Dosimetry: Estimates of changes in determination of D_w

Radiation Type	Relative change (%)	
ΔD_w for photons	-0.2	For low beam qualities.
	-0.5	For high beam qualities.
ΔD_w for electrons	-0.4	$(s_{w,air}\, p_{ch})_{^{60}Co}$
ΔD_w for protons and carbon ions	-0.5	

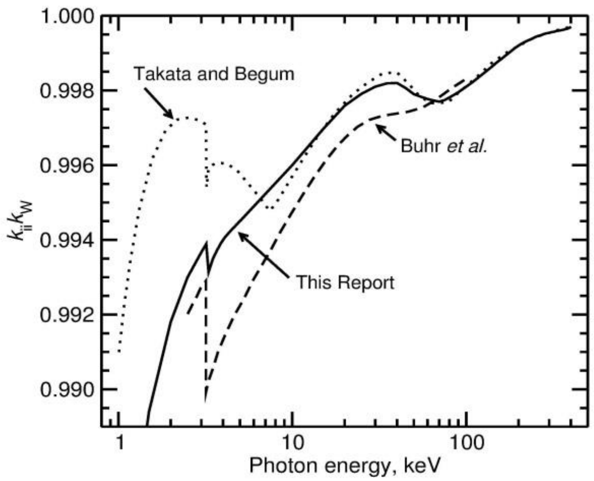
Corrections for Low-Energy X Rays



k_W corrects for rise in W_{air} at low <u>electron</u> energies



k_{ii} corrects initial ions that should not be included in air-kerma measurement



significant compensation in product of $k_{ii}\,k_W$

Thank You

There is of course more in the ICRU Report.
I’m not sure when it will be published.