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A Significant Correction Factor in Gamma Ray Dosimetry

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A Significant Correction Factor in Gamma Ray Dosimetry

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Softening of the gamma rays as they penetrate light materials may cause very large differences in the radiation doses absorbed in the samples and in the dosimeters. This is illustrated in the present paper by calculating the dose in 14 dosimeters and several other materials placed at distances of 0, 1, 2, and 4 relaxation lengths from a point isotropic ^{60}Co source embedded in a large water container. These calculations show for instance, that the doses in water, Lucite, Fricke dosimeter, lithium fluoride, poly(vinyl chloride) and 0.4M ceric sulfate solution at zero distance from the source are in the ratios: 100: 96: 100: 83: 92: 99; at a distance corresponding to $\mu_t \cdot r = 1$ the dose ratios are 100: 95: 100: 85: 124: 169; and at a distance corresponding to $\mu_t \cdot r = 4$ the similar ratios are: 100: 93: 101: 87: 162: 251.

Absorbed dose in a sample irradiated by gamma rays is usually determined by measuring the absorbed dose in a dosimeter; for instance, a Fricke dosimeter placed in the position of the sample. This absorbed dose in the dosimeter is, however, generally different from that in the sample. To arrive at the absorbed dose in the sample, corrections must be made for the difference. These corrections are partly caused by gamma electron non-equilibrium at the boundary, transfer of energy of excited states across the boundary, and partly caused by differences in mass energy transfer coefficients which are functions of the atomic number and the gamma ray energy. The corrections caused by boundaries will not be considered in this paper, but only the corrections caused by mass energy transfer coefficients.

In radiation dosimetry the energy absorbed per ml. of sample is usually the quantity of interest. To arrive at the energy absorbed per ml.

of the sample, the dose D_a in the dosimeter—*i.e.*, the Fricke dosimeter, is first multiplied by the ratio $\frac{\rho_s}{\rho_d}$, *i.e.*, the ratio of density ρ_s of the sample solution to the density ρ_d of the dosimeter solution. Secondly, the dose D_a is multiplied by the ratio $\frac{\mu_s}{\rho_s} \cdot \frac{\rho_d}{\mu_d}$, *i.e.*, the ratio of the mass energy transfer coefficients. These two correction factors are usually applied.

The third correction factor, which is the ratio of the adsorbed dose buildup factors in the sample and the dosimeter, is usually ignored, but is shown in this paper to be very important. The absorbed dose buildup factor is defined in this paper analogous to the dose buildup factor, a notation used when the unit roentgen was still the unit of radiation dose. This paper shows the magnitude of this third correction factor, which is caused by differences in gamma-ray attenuation coefficients and softening of the gamma-ray spectrum. As an illustrative example, the dose in different dosimeters is calculated as a function of the distance from a point isotropic cobalt-60 source in water.

Calculations of Absorbed Dose

The gamma-ray energy in rads per second absorbed in an infinitesimal volume $dx \cdot dy \cdot dz$ at the point $P(x, y, z)$ is given by

$$\begin{aligned} d &= 1.60209 \cdot 10^{-8} \int_0^{E_{\max}} E \cdot \frac{d\phi(E)}{dE} \cdot \frac{\mu_k(E)}{\rho} \cdot dE \\ &= 1.60209 \cdot 10^{-8} \int_0^{E_{\max}} \frac{dI(E)}{dE} \cdot \frac{\mu_k(E)}{\rho} \cdot dE \end{aligned} \quad (1)$$

where

d = dose rate in rads/sec. = 100 erg/gram sec.

E = photon energy in Mev.

$\phi(E)$ = photon flux density = the total number of photons of energy less than E which enter a sphere of cross-sectional area 1 cm.² per sec. at the considered point P . $\phi(E)$ is in units of cm.⁻² sec.⁻¹ (total number of photons per cm.² per sec.).

$\frac{d\phi(E)}{dE}$ = photon flux density spectrum = number of photons in the energy interval E to $E + dE$ which enter a sphere of cross-sectional area 1 cm.² per sec. at the considered point P .

$\frac{d\phi(E)}{dE}$ is in units of Mev.⁻¹ cm.⁻² sec.⁻¹ (number of photons per Mev. per cm.² per sec.).

$\frac{\mu_k(E)}{\rho}$ = mass energy transfer coefficient in cm.²/gram of the dosimeter at P for photons in the energy interval E to $E + dE$.
 ρ is the density in gram/cc.

$I(E)$ = the energy flux density or intensity—*i.e.*, the total energy of all the photons with energy less than E that cross a sphere of cross-sectional area of 1 cm.² per sec. at the point P . $I(E)$ is in units of Mev. · cm.⁻² · sec.⁻¹ (energy in Mev. per cm.² per sec.).

$\frac{dI(E)}{dE}$ = the energy flux density spectrum or intensity spectrum—*i.e.*, total energy of the photons in the energy interval E to $E + dE$ that cross a sphere of cross-sectional area of 1 cm.² per sec. at the considered point P · $\frac{dI(E)}{dE} = \frac{d\phi}{dE} \cdot E$ is in units of cm.⁻² sec.⁻¹ (energy in Mev. per Mev. per cm.⁻² per sec.).

The Absorption Coefficient. In Equation 1 the mass energy transfer coefficient $\frac{\mu_k}{\rho}$ should be used and not the mass energy absorption coefficient $\frac{\mu_a}{\rho}$ given by

$$\frac{\mu_a}{\rho} = \frac{\tau}{\rho} + \frac{\sigma_a}{\rho} + \frac{\kappa}{\rho} \quad (2)$$

where

$\frac{\tau}{\rho}$ = photoelectric mass attenuation coefficient in cm.²/gram.

$\frac{\sigma_a}{\rho} = \frac{\sigma_t}{\rho} \cdot \frac{E_e}{h\nu}$ the absorption component of the total Compton cross section in cm.²/gram, E_e is the average energy given to the electrons in the Compton process with total cross section $\frac{\sigma_t}{\rho}$ in cm.⁻²/gram for incoming photons of energy $h\nu$.

$\frac{\kappa}{\rho}$ = the cross section for the pair production in cm.²/gram.

The mass energy transfer coefficient is similarly given by

$$\frac{\mu_k}{\rho} = \frac{\tau_a}{\rho} + \frac{\sigma_a}{\rho} + \frac{\kappa_a}{\rho} \quad (3)$$

where

$$\frac{\tau_a}{\rho} = \frac{\tau}{\rho} \left(1 - \frac{\delta}{h\nu} \right) \quad (4)$$

$$\frac{\kappa_a}{\rho} = \frac{\kappa}{\rho} \left(1 - \frac{2mc^2}{h\nu} \right) \quad (5)$$

where

δ = average energy emitted as fluorescent radiation per photon absorbed in the photoelectric process.

$\frac{2mc^2}{h\nu}$ = is the correction for escaping radiation from the annihilation of the positron.

δ is mainly determined by the fluorescence yield ω_k in the K-shell. ω_k is, according to Hagedoorn and Wapstra (4) given by

$$\frac{\omega_k}{1 - \omega_k} = (-6.4 \cdot 10^{-2} + 3.4 \cdot 10^{-2} \cdot Z - 1.03 \cdot 10^{-6} Z^3)^4; \quad (6)$$

where

Z = atomic number

$\omega_k = \frac{\text{number K-shell vacancies}}{\text{number K-shell x-rays}}$

ω_k as a function of the atomic number (Z) is shown in Table I.

Table I. Fluorescent Yield

Atomic Number 2	Element	Fluorescent Yield $\omega_k \cdot 100 =$ $\frac{K_x \cdot 100}{K_x + K_{Au}}$	Electron Binding Energy in Kev.		Absorptions Coefficient in cm^2/gram in Water at the Gamma Energy
		in %	K-Shell	L-Shell	
8	O	0.18	.532		33,000
10	Ne	0.57	.867	.019	7,200
14	Si	2.7	1.839	.118	800
16	S	4.9	2.472	.193	320
20	Ca	12	4.038	.400	72
26	Fe	29	7.112	.842	13.5
29	Cu	39	8.972	1.100	6.8
30	Zn	43	9.659	1.196	5.4
40	Zr	70	17.998	2.532	0.76
50	Sn	83	29.200	4.465	0.157
56	Ba	88	37.441	5.987	0.075
58	Ce	89	40.444	6.549	0.062
60	Nd	90	43.568	7.126	0.053

In light elements δ is always small, because most of the energy is taken up by the Auger electrons and $\frac{\tau_a}{\rho}$ can then be replaced by $\frac{\tau}{\rho}$. As the atomic number increases, the fluorescent radiation increases. A portion of the fluorescent radiation, especially from the L-shell or the higher shells, is often absorbed within the dosimeter; for instance, the 1,000 e.v. x-rays from the L-shell in copper penetrate only $2 \cdot 10^{-4}$ cm. of water.

Therefore, in these calculations we have neglected this fluorescent radiation and used $\frac{\mu_e}{\rho}$ instead of $\frac{\mu_a}{\rho}$ in Equation 3. This approximation is adequate for samples and dosimeters containing atomic number $Z < 30$. But for samples containing high atomic number—*e.g.*, ceric sulfate solutions—this approximation in the calculations leads to an absorbed dose which is slightly too high. In case of ^{60}Co radiation, the pair production is negligible in light elements, while in cerium, the heaviest considered here, it is 0.8%.

The values of the absorption coefficients used in this report are those reported by Storm *et al.* (10).

Energy Flux Density Spectrum. $\frac{dI(E)}{dE}$ has been calculated for a point isotropic ^{60}Co source embedded in a large water container by Goldstein and Wilkins (3). (The nomenclature in this paper is that recommended by the International Commission on Radiological Units and Measurements (6), which differs from that used by Goldstein and Wilkins who used I for the same quantity as $\frac{dI}{dE}$ in this paper.) Corresponding energy buildup factors in water were measured by G. R. White (12), Van Dilla and Hine (2), Bibergal *et al.* (1), and by Sehested *et al.* (8). These experimental buildup factors were found to agree with the theoretically calculated ones within experimental and calculated accuracy of 10%. Weiss and Bernstein (11) studied the energy spectrum below 150 Kev. and found agreement with Spencer's and Fano's calculated values (9), whose calculations were the basis for the report by Goldstein and Wilkins (3). All this indicates that the intensity spectrum $\frac{dI(E)}{dE}$ reported by Goldstein and Wilkins for a point isotropic ^{60}Co source in water is fairly correct and it will, therefore, be used in Equation 1. The spectra are shown in Figure 1.

Calculation of Equation 1. Goldstein and Wilkins list only a few points on the spectral curves. We have graphically interpolated these points so that small intervals could be used in the numerical integration of Equation 1. Further, an extrapolation of the spectral values beyond the lowest value reported by Goldstein and Wilkins was done by assuming that at the low energies the spectral distribution is similar to that for a primary photon energy of 1 Mev.

Equation 1 was integrated numerically, because neither $\frac{dI}{dE}$ nor $\frac{\mu_k}{\rho}$ can be expressed accurately with simple functions. The widths of the energy intervals used in the integration were 0.01 Mev. from 0.025 Mev. to 0.175 Mev.; 0.0125 Mev. for photons of 0.1750 Mev. to 0.1875 Mev.; 0.025 Mev. for photons of 0.1875 Mev. to 1.2125 Mev.; and 0.0375 Mev.

for photons of 1.2125 Mev. to 1.2500 Mev. For the primary photons from ^{60}Co 1.17 Mev. and 1.33 Mev., an average energy of 1.25 Mev. was used.

Goldstein and Wilkins (3) do not list the photon intensity spectrum $\frac{dI}{dE}$ directly but the value of

$$4\pi r^2 \cdot \frac{dI_s(E)}{dE} \cdot \exp(\mu_t \cdot r)$$

where

$\mu_t = 0.0632 \text{ cm.}^{-1}$ is the total absorption coefficient in water at the primary photon energy E_0 .

We have, therefore, first calculated the value

$$d \cdot 4\pi r^2 \cdot \exp(\mu_t \cdot r) = 1.602 \cdot 10^{-8} \cdot 3.7 \cdot 10^{10} C \cdot$$

$$4\pi r^2 \cdot \exp(\mu_t \cdot r) \cdot \left[\frac{2.5 \exp(-\mu_t \cdot r) \cdot \mu_k(E_0)}{4\pi r^2 \cdot \rho} + \right. \quad (7)$$

$$\left. \int_0^{E_0} \frac{dI_s}{dE} \cdot \frac{\mu_k}{\rho} \cdot dE \right]$$

The first term in the bracket is the contribution from the primary gamma rays (1.17 and 1.33 Mev.) at the point P , r cm. from the point source and the last term is the contribution from the scattered gamma rays at the point P . d is the dose rate in rads per sec.; r is the distance in water from the point isotropic ^{60}Co source of C curies; $\mu_t = 0.0632 \text{ cm.}^{-1}$ is the total linear absorption coefficient in water for 1.25 Mev. photons; $\frac{dI_s}{dE}$ is the scattered gamma ray intensity spectrum; and $\frac{\mu_k(E)}{\rho}$ is the energy transfer coefficient in the dosimeter. It is assumed that the dosimeter is small enough not to change the energy intensity spectrum in the water at the point P , and that it is large enough to make the effect of gamma electron nonequilibrium negligible.

Definition of Absorbed Dose Buildup Factor. In the analysis of the dose variation, the concept of dose buildup factor is useful. The usual definition of dose buildup factor (3, 5, 7) limits its use to dose in an air dosimeter. The present definition of absorbed dose measured in rads, by which dose in any material or in any dosimeter is defined (6) makes the previous definition of dose buildup factor too restrictive. We will, therefore, replace the dose buildup factor by defining the absorbed dose buildup factor $B(r)$ for a given dosimeter in a given medium as the ratio of the actual absorbed dose in the dosimeter to the absorbed dose that would be measured in the dosimeter if there was no scattered radiation. The value of Equation 7 was, therefore, divided by the absorbed dose

rate from the unscattered photons, the first term on the right side in Equation 7. This quotient value we call $B(r)$, i.e.,

$$B(r) = \frac{\frac{\mu_k(E_0)}{\rho} \cdot I_0 + \int_0^{E_0} \exp(\mu_t \cdot r) \cdot 4\pi r^2 \frac{dI_s}{dE} \frac{\mu_k(E)}{\rho} \cdot dE}{\frac{\mu_k(E_0)}{\rho} \cdot I_0} \quad (8)$$

where $I_0 = 2.5$ Mev. per one disintegration of ^{60}Co .

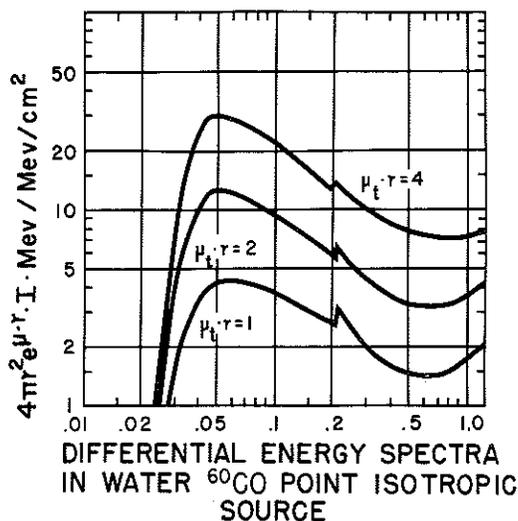


Figure 1. Energy spectra $\frac{dI}{dE}$ in water at a distance r corresponding to $\mu_t \cdot r = 1$; $\mu_t \cdot r = 2$; and $\mu_t \cdot r = 4$ from a point isotropic ^{60}Co source. The ordinate shows $4\pi r^2 \exp(\mu_t \cdot r) \cdot \frac{dI}{dE}$; the abscissa the photon energy in Mev.

The absorbed dose buildup factor $B(r)$ in Equation 8 is the ratio of the actual dose in the dosimeter at a point P , r cm. from a point isotropic ^{60}Co source imbedded in large water container, to the dose that would be measured at the same point if there were no scattered radiation. In this equation I_0 is the energy emitted by the source; I_s is the scattered radiation flux at P ; μ_t is the total absorption coefficient of water (0.0632 cm.^{-1}); and $\frac{\mu_k}{\rho}$ is the energy transfer coefficient in $\text{cm.}^2/\text{gram}$ in the dosimeter.

The integral in Equation 8 was calculated for ten elements common in applied dosimeters. These ten elements were H, C, O, Al, Si, S, Cl, Fe,

Cu, and Ce. The corresponding buildup factors calculated according to Equation 8 are listed in Table II.

Table II. Dose Buildup Factors in Elements at Different Distances in Water from a Point Isotropic ^{60}Co

Element	Buildup Factors at $\mu_t \cdot r =$			Element	Buildup Factors at $\mu_t \cdot r =$		
	1	2	4		1	2	4
*H 1	1.958	3.101	5.618	K 19	3.94	8.8	19.1
He 2	1.96	3.10	5.62	Ca 20	4.31	9.9	21.5
Li 3	1.96	3.11	5.64	Sc 21	4.71	11.2	24.4
Be 4	1.97	3.13	5.68	Ti 22	5.19	12.5	27.5
B 5	1.98	3.16	5.74	V 23	5.75	14.0	31.0
*C 6	1.995	3.201	5.850	Cr 24	6.17	15.6	34.7
N 7	2.02	3.27	6.01	Mn 25	7.00	17.3	39.0
*O 8	2.051	3.363	6.228	*Fe 26	7.66	19.24	43.29
F 9	2.10	3.50	6.59	Co 27	8.2	21.2	48.0
Ne 10	2.17	3.69	7.20	Ni 28	9.0	23.2	52.8
Na 11	2.25	3.92	7.62	*Cu 29	9.86	25.43	57.7
Mg 12	2.36	4.25	8.32	Zn 30	10.8	28	64
*Al 13	2.494	4.627	9.179	Br 35	16	43	97
*Si 14	2.665	5.115	10.32	Zr 40	23	62	138
P 15	2.86	5.65	11.50	Rh 45	31	85	190
*S 16	3.106	6.367	13.24	Sn 50	40	112	252
*Cl 17	3.38	7.14	15.04	I 53	45	130	295
A 18	3.61	7.90	17.00	*Ce 58	38.5	103.6	241.1

Interpolation of the Values of B. The energy absorption coefficient can be approximated by:

$$\frac{\mu_e}{\rho} = \frac{a(E) \cdot Z}{A} + \frac{b(E) \cdot f(Z)}{A} \quad (9)$$

where

Z = atomic number

A = atomic weight

$\frac{a(E) \cdot Z}{A}$ = Compton absorption

$a(E)$ = a function of the photon energy E , but independent of Z and A .

$b(E) \cdot f(Z)$ = photoelectric absorption

$b(E)$ = a function of the photon energy E but independent of Z and A .

$f(Z)$ = a function of the atomic number but independent of E

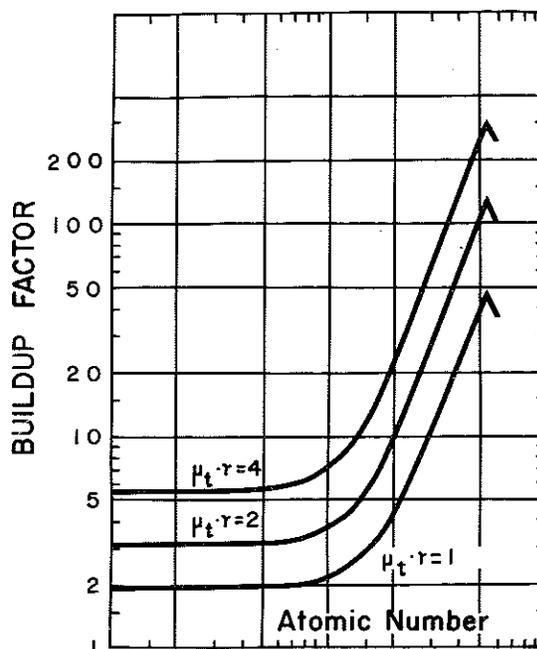


Figure 2. Absorbed dose buildup factors at distances r in water corresponding to $\mu_t \cdot r = 1$; $\mu_t \cdot r = 2$; and, $\mu_t \cdot r = 4$ from a point isotropic ^{60}Co source as a function of the atomic number Z

Table III. Dose Buildup Factors in Compounds at Different

Chemical Compound	Molecule Weight	$\frac{\mu_k}{\rho} \cdot 100$ in cm^2/gram at 1.25 Mev.
H_2O	18.015	2.975
LiF	25.937	2.471
$(\text{CH}_2)_n$	14.027	3.042
Lucite $\text{C}_5\text{H}_8\text{O}_2$	101.017	2.852
Polyvinyl Chloride $(\text{H}_3\text{C}_2\text{Cl})_n$	62.499	2.738
SiO_2	60.084	2.67
NaCl	58.453	2.563
H_2SO_4	98.076	2.706
FeSO_4	151.907	2.599
CuSO_4	159.600	2.587
$\text{Ce}(\text{SO}_4)_2$	332.240	2.630
SO_4^{2-}	96.06	2.6514
Bone (Z eff. = 13.8)		

The integral in Equation 1 can then for each distance r be written as:

$$d = a_1 \cdot \frac{Z}{A} + b_1 \cdot \frac{f(Z)}{A}; \quad (10)$$

where a_1 and b_1 are functions of the distance r from the source but independent of Z .

The buildup factor in Equation 8 can then be expressed as:

$$B(r) = 1 + a_2 + b_2 \cdot f(Z) \cdot Z^{-1} \quad (11)$$

insofar as the photoelectric absorption and the pair production can be neglected at 1.25 Mev. photon energy. a_2 and b_2 are functions of r , but independent of Z . The variation of $f(Z)$ was determined from the photoelectric absorption at $E = 0.045$ Mev. The values so determined were used to calculate the values of a_2 and b_2 for each distance that gave close fit to the more exactly calculated values for the ten elements mentioned above. Equation 11 was then used to interpolate B -values for other atomic numbers. The values so found, together with the more exactly calculated values, are reported in Table II, and Figure 2.

The Buildup Factor of a Chemical Compound or Mixture. The absorbed dose buildup factor $B(r)$ of a compound consisting of the elements X_1, X_2, X_3, \dots with the buildup factors B_1, B_2, B_3, \dots and mass energy transfer coefficients $\frac{\mu_1}{\rho_1}, \frac{\mu_2}{\rho_2}, \frac{\mu_3}{\rho_3}, \dots$ —at 1.25 Mev. photon energy, and

Distances in Water from a Point Isotropic ^{60}Co Source

<i>Buildup Factor at $\mu_t \cdot r = 0$</i>	<i>Buildup Factor at $\mu_t \cdot r = 1$</i>	<i>Buildup Factor at $\mu_t \cdot r = 2$</i>	<i>Buildup Factor at $\mu_t \cdot r = 4$</i>
1.000	2.033	3.311	6.106
1.000	2.072	3.435	6.415
1.000	1.986	3.176	5.792
1.000	2.006	3.234	5.928
1.000	2.738	5.288	10.722
1.000	2.338	4.182	8.141
1.000	2.944	5.928	12.146
1.000	2.385	4.315	8.450
1.000	4.261	9.622	20.357
1.000	5.246	12.402	27.324
1.000	17.414	45.572	105.134
1.000	2.405	4.928	11.946
	2.65	5.1	10.

Table IV. Buildup Factors in Dosimeters at Different

<i>Chemical Mixtures and Solutions</i>	<i>Weight Percent</i>	<i>Density</i>
Air Dry		
N ₂	75.56	0.00129
O ₂	23.15	
Ar	1.29	
Sulfuric Acid		
0.4M H ₂ SO ₄	3.832	1.0239
H ₂ O	96.168	
Sulfuric Acid		
0.005M H ₂ SO ₄	0.049	1.00025
H ₂ O	99.951	
Fricke Dosimeter		
0.001M FeSO ₄	0.015	1.0240
0.400M H ₂ SO ₄	99.985	
H ₂ O		
Fricke Dosimeter		
0.001M FeSO ₄	0.0152	1.0240
0.001M NaCl	0.0023	
0.400M H ₂ SO ₄	99.9825	
H ₂ O		
Ferrous Cupric Dosimeter		
0.001M FeSO ₄	0.015	1.002
0.010M CuSO ₄	0.159	
0.005M H ₂ SO ₄	99.826	
H ₂ O		
Ferrous Cupric Dosimeter		
0.006M FeSO ₄	0.091	1.011
0.060M CuSO ₄	0.950	
0.005M H ₂ SO ₄	98.959	
H ₂ O		
Ceric Dosimeter		
0.01M Ce(SO ₄) ₂	0.323	1.0279
0.40M H ₂ SO ₄	99.677	
H ₂ O		
Ceric Dosimeter		
0.10M Ce(SO ₄) ₂	3.12	1.066
0.40M H ₂ SO ₄	96.88	
H ₂ O		
Ceric Dosimeter		
0.40M Ce(SO ₄) ₂	10.53	1.262
0.40M H ₂ SO ₄	89.47	
H ₂ O		

Distances in Water from a Point Isotropic ^{60}Co Source

$\frac{\mu_k}{\rho} \cdot 100$ in cm. /gram at 1.25 Mev.	<i>Buildup</i> <i>Factor at</i> $\mu_t \cdot r = 1$	<i>Buildup</i> <i>Factor at</i> $\mu_t \cdot r = 2$	<i>Buildup</i> <i>Factor at</i> $\mu_t \cdot r = 3$
2.669	2.046	3.355	6.210
2.965	2.045	3.346	6.188
2.975	2.033	3.311	6.107
2.965	2.046	3.347	6.190
2.956	2.046	3.347	6.191
2.974	2.038	3.325	6.138
2.971	2.061	3.391	6.294
2.964	2.089	3.468	6.472
2.955	2.474	4.518	8.934
2.930	3.498	7.338	15.54

with the weight fractions A_1, A_2, A_3, \dots can be calculated according to

$$B(r) = \frac{B_1(r) \cdot \frac{\mu_1}{\rho_1} \cdot A_1 + B_2 \cdot \frac{\mu_2}{\rho_2} \cdot A_2 + \dots + \dots}{\frac{\mu_1}{\rho_1} \cdot A_1 + \frac{\mu_2}{\rho_2} \cdot A_2 + \dots} \quad (12)$$

In the present case, the average energy of 1.25 Mev. can be used. Several such values calculated using Equation 12 are shown in Tables III and IV and in Figures 3 and 4.

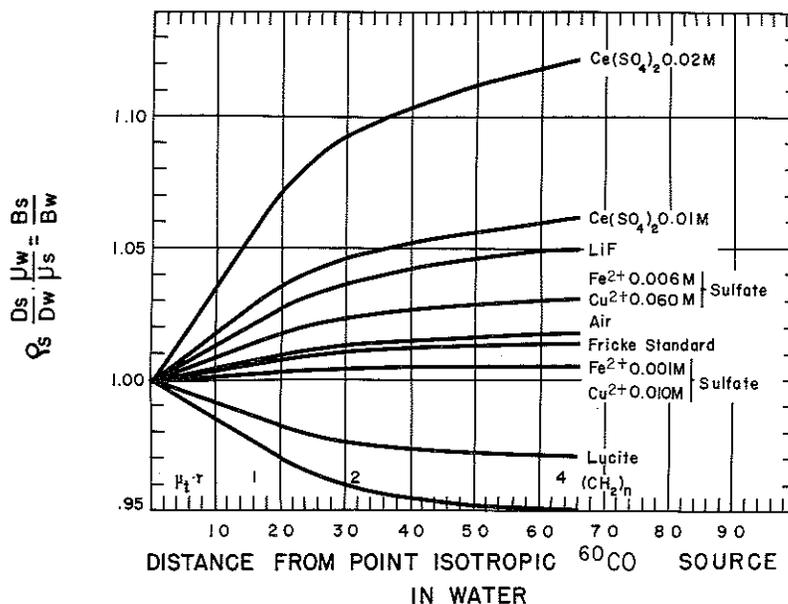


Figure 3. Absorbed dose buildup factors in different dosimeters relative to that of water as a function of the distance r in cm. from a point isotropic ^{60}Co source embedded in a large water container

Dose as a Function of the Distance from the ^{60}Co Sources. From Equations 7 and 8 we derive Equation 13 for the dose d in a dosimeter with an absorbed dose buildup factor B , r cm. from a point isotropic ^{60}Co source in water.

$$d = \frac{\mu_k}{\rho} \cdot B \cdot 1482 \cdot C \cdot \frac{e^{-\mu_t r}}{4\pi r^2} \text{ rads/sec.} \quad (13)$$

$\frac{\mu_k}{\rho}$, and B depend on the dosimeter, while the source strength C in curies ^{60}Co , the total absorptions coefficient $\mu_t = 0.0632 \text{ cm}^2/\text{gram}$ in water, and the distance r in cm. from the source are independent of it.

$\frac{\mu_k}{\rho}$, the energy transfer coefficient in cm^2/gram at the primary photon energy is almost equal to $\frac{\mu_e}{\rho}$, the energy absorption coefficient; B is found in Tables II, III, and IV.

It is illustrative to consider the ratio of the dose $d_s(r)$ in a dosimeter with an energy transfer coefficient $\frac{\mu_{ks}}{\rho_s}$ to the dose $d_w(r)$ in water with energy transfer coefficient $\frac{\mu_{kw}}{\rho_w}$ at the distance r cm. from the source. According to Equation 13 this ratio is given by:

$$\frac{d_s}{d_w} = \frac{\mu_{ks}/\rho_s}{\mu_{kw}/\rho_w} \cdot \frac{B_s(r)}{B_w(r)} = \frac{\mu_{ks}}{\mu_{kw}} \cdot \frac{\rho_w}{\rho_s} \cdot \frac{B_s}{B_w} \quad (14)$$

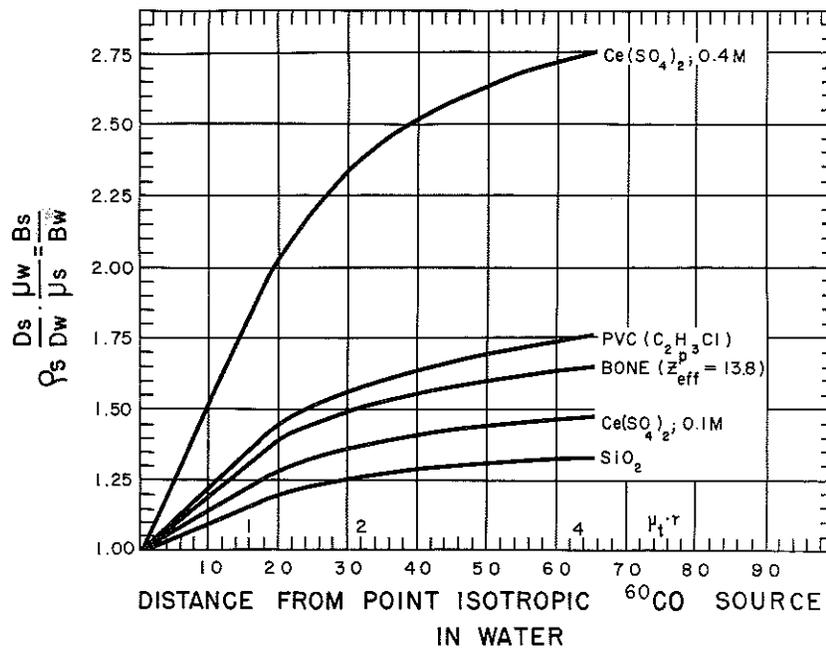


Figure 4. Absorbed dose buildup factors in different dosimeters relative to that of water as a function of the distance r in cm. from a point isotropic ^{60}Co source embedded in a large water container

The values of the energy transfer coefficients at E_0 can be found in the Tables by Storm *et al.* (10), while the ratio $\frac{B_s}{B_w}$ is shown for several dosimeters in columns 3, 4, and 5 of Table V, and the corresponding

Table V. The Absorbed Dose Buildup Factors and the Dose in Function of the Distance r in Water

Name	Formula	$\frac{B_s}{B_w}$ the buildup factors B_s relative to the buildup factor B_w of water at		
		$\mu_t \cdot r = 1$	$\mu_t \cdot r = 2$	$\mu_t \cdot r = 4$
Hydrocarbon	$(CH_2)_n$	0.977	0.959	0.949
Lucite	C_5H_8O	0.987	0.977	0.971
Draganić Dosimeter	0.1M $(COOH)_2$	1.000	1.000	1.000
Water	H_2O	1.000	1.000	1.000
Ferrous Sulfate	0.001M $FeSO_4$	1.002	1.004	1.005
Cupric Sulfate	0.010M $CuSO_4$			
Sulfuric Acid	0.005M H_2SO_4			
Fricke Dosimeter	0.001M $FeSO_4$ 0.4M H_2SO_4	1.006	1.011	1.014
Air	75.56% N_2 23.15% O_2 1.29% Ar	1.006	1.013	1.017
Ferrous Sulfate	0.006M $FeSO_4$	1.014	1.024	1.031
Cupric Sulfate	0.060M $CuSO_4$			
Sulfuric Acid	0.005M H_2SO_4			
Lithium Fluoride	LiF	1.019	1.037	1.051
Ceric Sulfate	0.01M $Ce(SO_4)_2$ 0.4M H_2SO_4	1.028	1.047	1.060
Quartz	SiO_2	1.150	1.263	1.333
Ceric Sulfate	0.10M $Ce(SO_4)_2$ 0.4M H_2SO_4	1.217	1.365	1.463
Poly(vinyl chloride)	H_3C_2Cl	1.347	1.597	1.756
Ceric Sulfate	0.4M $Ce(SO_4)_2$ 0.4M H_2SO_4	1.720	2.216	2.545

ratio $\frac{d_s}{d_w}$ in columns 6, 7, 8, and 9 of the same table. For other materials it may be derived by using Table II, Equation 12, and Equation 14.

Significance in Practical Problems. Close to the source, the Compton scattering of the primary gamma rays is the main process. In cobalt, for instance, the total Compton cross section is 0.054 cm²/gram; and the photoelectric cross section is 0.00028 cm²/gram at 1.25 Mev. This

**Dosimeters Relative to the Corresponding Values in Water as a
from an Isotropic ^{60}Co Point Source**

$\frac{d_w}{d_s}$; the dose d_s relative to the dose d_w of water at

$\mu_t \cdot r = 0$	$\mu_t \cdot r = 1$	$\mu_t \cdot r = 2$	$\mu_t \cdot r = 4$
1.023	0.999	0.981	0.971
0.959	0.946	0.937	0.931
0.999	0.999	0.999	0.999
1.000	1.000	1.000	1.000
1.000	1.002	1.004	1.005
0.997	1.002	1.008	1.011
0.897	0.902	0.909	0.912
0.999	1.013	1.023	1.030
0.831	0.847	0.862	0.873
0.996	1.024	1.043	1.056
0.897	1.032	1.133	1.196
0.993	1.208	1.355	1.453
0.920	1.239	1.469	1.616
0.985	1.694	2.183	2.507

means that the gamma ray spectrum close to the source is fairly independent of the material immediately surrounding the source. For example, the spectrum of the gamma rays after penetrating 1 cm. of cobalt with density ρ_{Co} is the same, or very similar, to the spectrum of the gamma rays after penetrating $\frac{18}{10} \cdot \frac{27}{59} \cdot \rho_{\text{Co}} = 7.4$ cm. of water except for the very lowest end of the spectrum. If this gamma ray spectrum then penetrates a few cm. of water, the low energy portion of the gamma ray

spectrum would be fairly well re-established. In many experiments the scattering of the gamma rays in the source, source encapsulation, surrounding ^{60}Co slugs, and in the sample and sample containment is of this magnitude. The effect discussed in the present paper is therefore of great significance in many experiments.

Let us assume that we want to measure the G -value, number of molecular changes per 100 e.v., of $\text{Ce}^{4+} \rightarrow \text{Ce}^{3+}$ in a ceric-sulfate solution as a function of the concentration. We measure the dose in a Fricke dosimeter vial or ferrous-cupric dosimeter vial at the same place as the vial containing the ceric solution, and then, as is usual, we correct for the difference in the energy transfer coefficient at 1.25 Mev. and for the difference in density of the solutions. However, as shown in Equation 14 and in Table V and Figures 3 and 4, these corrections are entirely inadequate because of the large difference in buildup factors. For 0.4M ceric sulfate solution, the correction caused by the buildup factor is 72% at $\mu_t \cdot r = 1$; 122% at $\mu_t \cdot r = 2$; and 155% at $\mu_t \cdot r = 4$.

If the dose is corrected for the difference in energy transfer coefficient at 1.25 Mev. and for the differences in density of the solutions but not for the differences in buildup factors; the G -value, even if actually constant, would behave as if it increased with concentration. This may partly explain the great increase in the G -values with concentration of ceric sulfate observed in the past by some authors. For poly(vinyl chloride) the buildup factors differ also greatly from those of water as is seen in Table III. This difference in buildup factors may explain some of the difficulties encountered in its use in gamma-ray facilities.

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