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EXPERIMENTAL DETERMINATION OF KERMA FACTORSAT $E_n \approx 15$ MeV

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Abstract

Experimental values for the kerma per unit fluence at the neutron energy, $E_n = 15$ MeV, have been determined for graphite, Mg, and Fe. Ion chambers of small size with walls of these materials were employed, and were filled with a variety of gases-- N_2 , CO_2 , Ne, Ar, Kr, and Xe. A calibrated neutron source was employed, allowing a straightforward determination of the kerma per unit fluence. The values found were:

Graphite: $2.25 \pm 0.49 \times 10^{-9}$ rad cm^2/n

Mg: $1.52 \pm 0.50 \times 10^{-9}$ rad cm^2/n

Fe: $0.59 \pm 0.23 \times 10^{-9}$ rad cm^2/n .

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An ion chamber is generally designed to respond in a radiation field to reflect the generation of charged particles in the chamber wall. These particles generate ions within the gas, the charge from which is interpreted to yield the field intensity, if one knows the chamber parameters. Conversely, if the field intensity is known, the chamber parameters may be inferred. The latter approach is followed here.

The quantity under study is the kerma per unit fluence, or kerma factor, in a neutron field. The kerma of a material is defined as the quotient of the sum of the initial kinetic energies of all the charged particles liberated by indirectly ionizing particles in an incremental mass, Δm , divided by Δm .¹ The kerma is seen to be the component of the radiation dose not due to gamma ray interactions within the irradiated sample. Generally in samples thin to gamma ray absorption, the radiation dose, or heating, will be primarily determined by the kerma.

Considerable attention has been given to the kermas for tissue materials exposed to neutrons of various energies (c.f. Ref. 1). Ample data has accrued for neutron energies associated with the fission process, but attention to D-T neutrons ($E_n = 14$ MeV) has been comparatively modest. Since these neutrons are becoming more important as progress is made in fusion programs, the need grows to be able to determine their engineering effects on structural materials as well as the low Z elements found in tissue.

Recent efforts at LLL have made available a calibrated D-T neutron source of high intensity well suited for experimental determination of kerma factors.² Straightforward exposure of ion chambers with walls of

selected materials and various gas fillings provides the data necessary for determination of the kerma factor for the wall material.

Theory

The effective volume of an ion chamber is easily found by exposure to a calibrated gamma ray source. The Bragg-Gray principle relates the dose in the chamber wall, E , to the collected charge, Q ,

$$E = \frac{S_g^W QW}{M_{\text{gas}}} = \frac{S_g^W \cdot Q \cdot W}{\rho_{\text{gas}} V} \quad (1)$$

Here, S_g^W is the mass-stopping-power ratio for the secondary charged particles in the chamber wall relative to the chamber gas, Q is the charge collected, W is the mean energy required to produce an ion pair in the gas volume, and M_g , ρ_g , and V are the gas mass, density, and effective gas volume, respectively.

In a gamma-ray field of known intensity the wall dose is simply:

$$D_{\text{wall}} = 0.869 \text{ R (roentgens)} \times \frac{(\mu/\rho)_{\text{wall}}}{(\mu/\rho)_{\text{air}}} \quad (2)$$

If the walls are thin to gamma rays, and in a free field environment, we may use dose and kerma equivalently. The chamber volume is then:

$$V = \frac{S_g^W QW}{\rho_g \cdot .869 \text{ R } (\mu/\rho)_w / (\mu/\rho)_{\text{air}}} \quad (3)$$

If we assume that the effective chamber volume does not change when employed in a neutron field, the response in the neutron field is:

$$D_n = \frac{(S_g^W)_n Q_n W_n}{\rho_n V_n} \quad (4)$$

$$\therefore \left(\frac{D_n}{Q_n} \right) = \frac{(S_g^W)_n \cdot \rho_g \cdot W_n (\mu/\rho)_{\text{wall}}}{(S_g^W)_\gamma \cdot \rho_n \cdot W_\gamma \cdot (\mu/\rho)_{\text{air}}} \times .869 \left(\frac{R}{Q} \right)_\gamma \quad (5)$$

If we have a calibrated ion chamber, so that (Q_n/ϕ_n) (coulombs $\text{cm}^2/\text{neutron}$) is known, the kerma per unit fluence is simply:

$$K.F. \equiv \frac{D_n}{\phi_n} = \left(\frac{D_n}{Q_n} \right) \cdot \left(\frac{Q_n}{\phi_n} \right) \quad (6)$$

For a particular ion chamber at LLL, the calibration factor is known to be:

$$\left(\frac{Q_{n,TE}}{\phi_n} \right) = 2.18 \times 10^{-18} \text{ C cm}^2/\text{n} \quad (7)$$

at 20°C and 760 Torr, for 15 MeV neutrons. With that chamber, $\phi_n (\text{n/cm}^2)$ is determined. The chamber under investigation is then operated at the same spatial position for a given number of monitor counts to yield a value for $(Q_{n,i})$. The kerma per unit fluence may then be solved with Eq. 6, utilizing Eq. 5.

The wall-generated charged particles are assumed to traverse the cavity, depositing only a small fraction of their energy in transit. Where the gas kerma factor differs markedly from that in the wall, the ion chamber cavity should be small with respect to the ranges of the wall-generated charged particles, to minimize this correction factor.⁴ Caswell has treated the more general case involving charged particles which originate or stop in the gas, for a T.E. plastic chamber, and shows clearly their importance when dealing with lower energy neutrons (e.g. 1 MeV).

Recently, kerma factors have been calculated from basic cross-sections, and tabulated for materials important to tissue neutron dosimetry.⁵ Also at LLL, the NDL cross-section set, which also includes energies generated in the nuclear interactions,⁶ permits straightforward generation of the kerma factors:

$$\text{Kerma factor at } E_j \left(\frac{\text{erg cm}^2}{\text{gm}} \right)$$

$$\begin{aligned}
&= \sum_i g_i \frac{{}^i\sigma_{t,ij} {}^i\epsilon_{L,i}}{A_i} \times 6.023 \cdot 10^{23} \times 1.601 \times 10^{-6} \\
&= 9.64 \times 10^{17} \sum_i g_i {}^i\sigma_{t,i} {}^i\epsilon_{L,i}/A_i,
\end{aligned}$$

where g_i = mass fraction of isotope i

${}^i\sigma_{t,ij}$ = total cross-section of isotope i , at E_j (cm^2)

${}^i\epsilon_{L,i}$ = local, or charged particle energy deposited per
interaction for isotope i , at E_j (MeV)

A_i = atomic weight of isotope i

Bob Howerton has generated kerma factor tables for many materials treated
in Vol. 16 of UCRL- 50400.⁷ Single values may be found conveniently with
the above expression.

Dosimeters

In the present study, four spherical ion chambers, kindly made
available by Dick Griffith of the Hazards Control Department, were
employed. Table I lists their physical characteristics, and their
gamma calibration factors using a ${}^{60}\text{Co}$ source. The chambers were
manufactured by EG&G, Santa Barbara.

Table I. Characteristics of Ion Chambers.

Chamber	I.D. (cm)	Wall Thickness (cm)	Gas Fill	Calibra- tion (R/coul)*	Calculated Volume (cm ³)
Tissue Equiv. (IC-17)	1.27	0.51	Air	3.36×10^9	1.00
			TE gas	2.93×10^9	0.99
Graphite (IC-17G)	1.68	0.30	Air	1.38×10^9	2.30
			CO	9.69×10^8	2.09
Magnesium (IC-17M)	1.66	0.31	Air	1.31×10^9	2.30
			Argon	9.30×10^8	2.20
Iron (IC-17I)	2.16	0.069	Air	5.51×10^8	5.17
			Argon	3.69×10^8	5.23

*760 mm Hg, 22°C.

The sixth column lists chamber volumes calculated from Eq. 3. The W_e values were taken from Myers,⁸ the stopping power data from Berger and Seltzer,⁹ and the (μ/ρ) ratios from Sinclair.¹⁰ The discrepancy in the two cavity volumes for graphite casts suspicion on the carbon parameters employed. Excellent agreement is found for the two gas fills for iron, which received the major attention in the present study.

The chambers were operated at 300 V.D.C., and runs were repeated with opposite polarity and sufficient delay to assure stabilization and adequate purity of gas flow. For exposure to neutrons, gases ranging from He to Xe were employed. The He data was abandoned because the data could not be reproduced satisfactorily. In retrospect this should not have been surprising since we made no attempt to purify the gas, but simply flowed it through the system. Others have noted the necessity for very high purity to avoid contaminant ionization which acts to reduce W_e .¹¹

The collected charge was integrated by a very stable commercial electrometer. Room background was recorded and corrections were made.

The iron chamber was most sensitive to this correction, fortunately small.

Neutron Source

The ICT accelerator at MLL¹² furnished an ample flux of 15-MeV neutrons for this study, generating about 3×10^{12} n/sec. The deuterons were accelerated to 400 KeV, producing 15 Mev neutrons in the forward direction. No shields or collimators were employed local to the source or detectors, but a water tank was situated about one meter above the source to reduce skyshine from the facility. Relative source output was measured with two permanently positioned proton recoil counters. The tissue-equivalent ion chamber studied earlier² provided the means of standardizing the facility neutron output and the conversion factors of the recoil counters.

Experimental Results

Each ion chamber was operated in the neutron field with varying gas fillings during three independent runs spread over a five month period with reproducibility within about five percent. The D-T reaction does not generate gamma rays, but unfortunately the high energy neutrons interact with the source backing and local structure, and the massive water tanks which are positioned to reduce skyshine. Measurements were made, primarily with the iron ion chamber with Xe gas filling, which was expected to have the lowest neutron : gamma sensitivity, to delineate the background. A 24 cm long cylindrical iron rod of 2.5 cm diameter was positioned as a shadow shield between source and detector. The resultant signal, if interpreted as due solely to secondary gamma rays, is

easily translated to (MeV of gammas/source neutron) since the gamma sensitivity of the chamber may be inferred from the gamma calibrations.¹³ The equivalent source gamma strength for three different source-detector spacings were:

ΔR (cm)	Gamma MeV per Source Neutron
25	0.19
50	0.51
100	0.93

Clearly, if the secondary radiation is due to gammas, we do not have the gamma ray source at the location of the neutron source. Rather it appears to be distributed over a rather large region.

Also we see that source-detector distances should be minimized, consistent with accurate measurement of these distances. One limiting factor is the uncertainty in the distance from the actual source to the outer surface of the target assembly. The increment of ~3 mm is uncertain to ~1 mm. Surface of target assembly to surface of ion chamber measurements were also uncertain to no more than 1 mm.

In the present study, residual signals not recorded during beam-on time were considered as background, and deleted. The runs were typically 2.5 minutes during which time 5.00×10^5 counts were recorded on a proton-recoil counter.

We also considered a gamma ray background increment which would originate in the ion chamber wall through (n, γ) processes. This should be proportional to the wall thickness. Accordingly we added ~3.5 gm of iron to the outer surface of the iron chamber which is about half the

chamber wall mass. The signal dropped about 1%, indicating a negligible contribution from the postulated source.

The collected charges for each (detector/gas fill) combination were corrected to exclude room background, including a modest increment due to time dependent room activation, and were corrected to 20°C and 760 Torr conditions. Eq. 6 was then applied in the manner described. Table II lists the specific parameters incorporated in Eq. 5.

Table II. Ion chamber parameters.

Material	$\left(\frac{dE}{dX}\right)_\gamma$ $\left(\frac{\text{MeV} \cdot \text{cm}^2}{\text{gm}}\right)$	$\left(\frac{dE}{dX}\right)^A$ $\left(\frac{\text{MeV} \cdot \text{cm}^2}{\text{gm}}\right)$	W_e (eV)	W_i (eV)	$\frac{(\mu/\rho)_{\text{wall}}}{(\mu/\rho)_{\text{air}}}$
TE gas	1.93	167.6	29.2	31.4	
Air	1.68	141.7	33.73	35.0	
N ₂	1.68	141.7	34.6	36.5	
CO ₂	1.68	142.4	32.9	34.5	
Ne	1.60	124	36.2	32.15	
Ar	1.40	96.1	26.2	26.35	
Kr	1.28	72.2	24.3	24.0	
Xe	1.21	58.5	21.9	22.8	
TE plastic	1.92	166.8			1.111
Graphite	1.65	146.1			1.004
Mg	1.55	116			0.989
Fe	1.39	89.8			0.940

*For 2 MeV protons.

The inferred kerma per unit fluence values for $E_n \approx 15$ MeV are listed in Table III. For any wall material, we would hope to see similar K.F.

values. The TE plastic values vary slightly, and are reasonably close to that inferred from basic cross-sections. The value based on updated ICRU-13 numbers reported earlier² was 7.21×10^{-9} rad cm²/n. The (TE/Xe) value is essentially that with air in the chamber, suggesting a passive role played by the gas in the TE ion chamber.

Table III. Kerma per Unit Fluence for Four Ion Chamber Wall Materials $\left(\frac{\text{Rad} \cdot \text{cm}^2}{\text{neutron}} \right) \times 10^9$

Gas	TE Plastic	Graphite	Mg	Fe
Air	7.40	--	--	--
N ₂	7.62	2.28	1.69	2.90
CO ₂	--	1.83	--	--
Ne	--	2.64	1.90	0.974
Ar	--	1.55	1.09	0.483
Kr	--	--	0.835	0.384
Xe	7.43	0.965	0.946	0.455

For the graphite, Mg, and Fe chambers, a clear trend is seen where the K.F. values decrease as the atomic weight increases. For each ion chamber, the K.F. value is highest when filled with Ne.

Discussion

The specific character of the charged particles generated in the wall materials deserve attention. If we assume them to be described by the stopping power data of Table II, a crude figure of merit that indicates the likelihood of wall-generated particles stopping in the gas is:

$$\Delta E_i^* = \left(\frac{dE}{dx} \right)_i \cdot \rho_i \cdot (\text{inner diameter})$$

which is simply the energy lost in traversing the longest path in the gas. For the (Fe/Xe) combination, $\Delta E^* = 0.73$ MeV, a modest value if protons of high energy are produced. On the other hand, if alpha particles are generated, the stopping power varies for particles of equal velocity as Z^2 where Z is the charge of the projectile, so here we would find 8.0 MeV alpha particles losing 2.9 MeV in crossing the Fe/Xe chamber. The elastic and inelastic collisions give rise to heavy ions with very high wall and gas stopping powers. Hopefully the gas would have similar cross-sections to compensate.

The Fe cross-sections and energy production factors which form the basis of Ref. 6 suggest that the (n,p) cross section, with a $Q = -1.9$ MeV plays an important role here. Also, the $^{24}\text{Mg}(n,p)^{24}\text{Na}$ reaction ($Q = -3.02$ MeV) accounts for ~50% of the charged particle energy production. On the other hand, the $^{12}\text{C}(n, n')^3\alpha$ reaction accounts for over half of the charged particle energy production and these alpha particles should be quite soft.

If $(K.F.)_{\text{gas}} < (K.F.)_{\text{wall}}$, the measured K.F. should fall below the wall K.F. Similarly, if $(K.F.)_{\text{gas}} > (K.F.)_{\text{wall}}$, the opposite should be true. The gas $(K.F.)$ may be directly found or derived from the N.B.S. $\frac{5}{6}$ calculations or those of Howerton, for many of the gases. We list these, along with the wall materials at $E_n = 15$ MeV:

Material	K.F. $\left(\frac{\text{Rad cm}^2}{n}\right) \times 10^9$	
	Ref. 5	Ref. 6
N	2.60	2.86
C	2.74	2.17
O	2.00	1.65
CO ₂	2.20	1.79
Ar	0.336	0.222
Mg	1.50	0.585
Fe	0.470	0.249

The N.B.S. values were interpolated. The K.F. for Xe should be well below that for Fe, since it varies as A^{-1} , unless that factor is offset by large charged-particle production cross-sections and energies. Fortunately, Argon was evaluated, as was N, C, and O. We may then make use of the inequalities above. Certainly the K.F. values for chambers with Xe filling may be viewed as lower limits of the $(K.F.)_{\text{wall}}$.

Accordingly, the K.F. values at $E_n = 15.0$ MeV for the wall materials follow from Table III, and are compared to predictions in Table IV. The experimental uncertainties are dominated by the scatter among the K.F. values, and include a 7% uncertainty for the absolute flux value and 10% for uncertainties in parameters such as the W_i 's. In the case of the Fe chamber, the Fe/Ar value was weighted to be four times more important than the values with other gas fills.

Table IV. Experimental and calculated kerma per unit fluence at $E_n = 15.0$ MeV ($\text{Rad cm}^2/\text{n}$) $\times 10^9$

Material	Exp.	Calc. (Ref. 5)	Calc. (Ref. 6)
C	2.25 ± 0.49	2.74	2.17
Mg	1.52 ± 0.50	1.50	0.585
Fe	0.59 ± 0.23	0.470	0.249

The graphite K.F. of 2.25×10^{-9} $\text{rad cm}^2/\text{n}$ does not conflict with either prediction but does tend to favor the ENDL set.⁶ The magnesium finding is in clear agreement with the NBS value, and is markedly higher than the ENDL-based value. Here the large discrepancy between the two predictions illustrate the virtue of integral experiments such as these. Finally, we see a measurement for $(\text{K.F.})_{\text{Fe}}$ which is very much larger than the ENDL prediction and also above the NBS value, although within experimental uncertainties.

One popular approach to the challenge of mixed-field dosimetry is the employment of ion chambers with differing neutron to gamma ray sensitivity ratios. The present data may be interpreted to extract this ratio for the many different chamber-gas combinations. The reference ratio was that found for the (TE chamber/air) combination, and the specific form was:

$$T_{\text{TE,air}} = (Q_n \text{ cm}^2/\text{n}) / (Q_\gamma/R).$$

For each combination in turn, the gamma calibration factor was found where it had not been measured according to the scheme described earlier.¹³ The relative sensitivity, $S_{i,j} = T_{i,j} / T_{\text{TE,air}}$, is listed in Table V.

Table V. Relative sensitivities of various chamber/gas combinations at $E_n = 15$ MeV.

Chamber	Gas	N ₂	CO ₂	Ne	Ar	Kr	Xe
TE		1.002	--	--	--	--	0.631
Graphite		0.333	0.265	0.425	0.195	--	0.0828
Mg		0.298	--	0.367	0.166	0.113	0.0978
Fe		0.215	--	0.224	0.0873	0.0579	0.0525

The T.E. ion chamber used here is designed and was shown to respond uniformly to a delivered dose whether due to neutrons or gammas. The manner of normalization shows therefore that the (Fe/Xe) combination is ~5% as sensitive to 15 MeV neutrons as a T-E chamber filled with air. It was for this reason that the (Fe/Xe) combination was employed most heavily in the determination of the room background.

The findings of Kuchnir, et al.,¹⁵ are in a convenient form for comparison. They also illustrate the dependence of relative sensitivity on neutron energy and gas fill. At $E_n = 15$ MeV, their relative neutron sensitivities are:

	Ref. 15	Table V
C/air :	0.39	
C/O ₂ :	0.34	
C/CO ₂ :	0.295	0.265
C/Ar :	0.29	0.195
Mg/Ar :	0.21	0.166

Their Mg ion chamber had a 0.5 cc cavity and the graphite chamber had a 2 cc cavity. The largest discrepancy is associated with the C/Ar combination.

The room background, discussed earlier, was estimated to be equivalent to 0.19 (gamma MeV/source neutron) for a nominal source-detector spacing of 25 cm. The contribution from the backing of the rotating target and adjoining materials can be estimated in a straightforward way. The Amzirc (copper alloy) target backing is 1.0 mm thick, the water layer is estimated at 0.3 mm thickness, and the stainless steel water spreader is 0.2 mm thick. If we assume an infinite planar geometry and an isotropic source and consider first the Amzirc backing, the integral gives:

$$\frac{\gamma \text{ MeV}}{\text{neutron}} = \frac{\sum \epsilon_{\gamma,i} \sigma_i}{2\sigma_{\text{total}}} \left[1 - E_2 \left(\frac{T}{\lambda_{\text{Tot}}} \right) \right]$$

where: $\epsilon_{\gamma,i}$ = Mev produced in reaction i.

σ_i = partial cross section.

σ_{total} = total cross section.

T = thickness of Amzirc backing

λ_{total} = total mean free path in Amzirc.

E_2 = exponential integral of second order ¹⁶;

$$E_2(x) = x^{-1} \int_x^\infty \frac{e^{-t}}{t^2} dt$$

¹⁶
For small values of x,

$$1 - E_2(x) = -x \ln(gx) + x + (x^2/2) - (x^3/12) \dots,$$

where: $g = 1.7811$.

Taking the nuclear parameters from Ref. 6, we find for the Amzirc alone 0.15 γ MeV/neutron generated local to the source. The water adds 0.01 γ MeV/n and the spreader an additional 0.03 γ MeV/n, summing to

0.19 γ MeV/n which is in excellent agreement with the experimental background value for source-detector spacing of 25 cm.

Recommendations and Conclusions

An effort has been made to determine values for kerma per unit fluence in a 15 MeV neutron field of known intensity, for selected materials. Ion chambers of small size, having walls of tissue-equivalent material, graphite, magnesium, and iron, were filled with a variety of gases--N₂, CO₂, Ne, Ar, Kr, and Xe.

The kerma per unit fluence for 15 MeV neutrons was found to be:

Graphite: $2.25 \pm 0.49 \times 10^{-9} \text{ rad cm}^2/\text{n.}$

Mg: $1.52 \pm 0.50 \times 10^{-9} \text{ rad cm}^2/\text{n.}$

Fe: $0.59 \pm 0.23 \times 10^{-9} \text{ rad cm}^2/\text{n.}$

An experimental approach which seeks to reduce the incremental energy deposition within the chamber cavity of wall-generated charged particles is recommended. Further the kerma per fluence of the fill gas should match reasonably closely the wall value. Chambers with smaller dimensions would help in this regard. Also smaller source-detector distances would improve the background problem, but add somewhat to geometric uncertainties. Thinner chamber walls could reduce the gamma ray response without affecting the neutron response.

A Monte Carlo capability which explicitly treats the flight of the charged particles would help greatly on a number of counts. Detector design could be optimized. More important, analysis in the spirit of Caswell,⁴ in a more comprehensive manner, could be accomplished.

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$$\gamma (R/Q)_{Xe}^{Fe} = \frac{S_{Xe,Y}^{air} W_{Xe,Y}}{\gamma_{Xe} W_{air,Y} \rho_{Xe}} \frac{\rho_{air}}{\rho_{Xe}} \gamma (R/Q)_{air}^{Fe}$$
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