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$\bar{W}$ Comparisons for
Al50 Plastic-Equivalent
Gases, TE Gas, and Air

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Introduction

As part of our continuing evaluation of Al50 plastic-equivalent gases for neutron dosimetry, we have measured ionization ratios which are related to $\bar{W}$ ratios between gases in the $p(66)\text{Be}(49)^*$ neutron beam at the Fermilab. Additionally we have extended our earlier measurements (DeLuca, et al., 1980) at the U.W. gas target $^3\text{H}(d,n)^4\text{He}$ neutron source to include an uncollimated beam geometry with ion chambers close to the target. Observed differences from the earlier results can probably be explained on the basis of neutron spectra, which await further determination.

* Generated by 66 MeV protons incident on a Be target having a thickness in which 49 MeV is dissipated before the protons leave the rear surface, assuming no nuclear collisions occur.

Gases

The gases studied include those reported previously (Awschalom and Attix, 1980; DeLuca et al., 1980) and a new mixture (A150 Mix 5), which was devised primarily to reduce electron attaching effects, if present, thus improving pulse counting properties. The mass compositions of three of the gas mixtures are given in Tables I and II. Dry, oil-free compressed air was used as a fourth gas. No differences have been observed between ionization results obtained with tank air vs static ambient air under identical irradiation conditions. The calculated densities of the four gases at 0° and 760 torr, assuming them to be "ideal" gases, are listed in Table III.

Each gas was flowed through its own gas-delivery system, consisting of a flow meter (Gilmont model 400102) and approximately two meters of copper tubing of 1 mm bore leading to the ion chambers. Gases were flowed continuously even when the tubing was not connected to an ion chamber, to eliminate contamination by ambient air. The ion chambers were connected sequentially to the different gases, purged at a high flow rate ($\sim 100 \text{ cm}^3 \text{ min}^{-1}$ for one or two minutes) and then operated at a constant flow rate in the range between 20 and $60 \text{ cm}^3 \text{ min}^{-1}$. No flow-rate-dependent effects were observed at these rates.

It will be seen in Tables I and II that the TE gas mixture employed for these measurements was only an approximation to standard methane-based TE gas (40.6% CH_4 , 55.9% CO_2 , and 3.5% N_2 , by weight, with $\rho = 1.1415 \text{ g/l}$ at STP). However the small differences in composition should be negligible in their effect on $\bar{W}$ values. (That incorrectly mixed tank of Matheson gas was subsequently removed from service.)

Ionization Chambers

Five ionization chambers of Al50 plastic in four different sizes were used in the measurements. Wall thicknesses were 5 mm for the 14 MeV neutron measurements, except for chamber e below (1.5 cm). For the Fermilab measurements all chamber walls were increased to 1.5 cm of Al50 plastic of density $\rho = 1.126 \text{ g/cm}^3$. The ion chambers employed were:

- a) 0.3 cm^3 flat chamber with its collecting volume inset into the front of a solid Al50 plastic cylinder 2.5 cm thick and 36 cm in diameter. Designed and constructed by J. J. Spokas (Illinois Benedictine College) in consultation with Fermilab personnel. The chamber had a collecting volume 1 cm in radius and a plate separation of 1 mm, (also taken as mean chord length $\bar{\ell}$). The front (input) wall was 0.5 mm of Al50 plastic, augmented to a thickness of 5 mm by an added disc of Al50 plastic. The chamber had two gas connections, allowing not only monitoring of the entrance gas flow rate as already discussed, but also verification of the exit flow (through a shallow bubbler). This was true also of chambers (d) and (e).
- b) 1 cm^3 spherical ion chamber, Model IC-17, Serial No. 193TG (EG & G, Inc., Goleta, CA, 93017). Wall thickness: 0.57 g/cm^2 . This chamber had its gas exit hole in the chamber wall itself. To avoid backflow of ambient air, the chamber was enclosed in a vented, loosely-fitting thin rubber envelope to provide a flow-gas atmosphere in the immediate surroundings. This was done also with the next chamber listed (c).

- c) 1 cm³ spherical ion chamber, Model IC-17, Serial No. 356RTG
(Far West Technology, Inc., Goleta, CA, 93017). Wall thickness: 0.57 g/cm². Mean chord length $\bar{\ell}$ = 8.3 mm.
- d) 8 cm³ spherical ion chamber, made at University of Wisconsin.
Wall thickness: 0.56 g/cm². Mean chord length: $\bar{\ell}$ = 16.5 mm.
- e) 80 cm³ spherical ion chamber, Model No. IC-80, Serial No. 396-8TG (Far West Technologies, Inc.). Wall thickness: 1.5 cm = 1.69 gm/cm². Mean chord length $\bar{\ell}$ = 35.6 mm.

Measurements at the Gas Target Neutron Source

The University of Wisconsin Gas Target Neutron Source (GTNS) has been described elsewhere (DeLuca et al., 1978). Its neutron output was monitored by an annular cylindrical ion chamber snugly fitting around the target container. The charge from this monitor chamber was measured by means of an Ortec Model 439 current digitizer. The other ion chamber charge outputs were measured for up to three chambers simultaneously by three separate Keithley 616 electrometers. Integration times were typically 100 sec.

Source-to-chamber distances were roughly 30-40 cm relative to the mid-point of the gas target, as indicated in Figs. 1 and 2. Each chamber remained firmly fixed in position during the whole sequence of measurements, so that the results obtained with different gases could be validly compared.

Shielding walls were as close as 20 cm from the ion chambers (see Figs. 1 and 2), and it may be assumed that their radiation environment contained a significant admixture of low-energy scattered neutrons, as well as capture γ rays. The earlier measurements of $\bar{W}$ reported by DeLuca et al. (1980) were done with the chambers located in a collimated neutron beam outside of the shield, where degradation of the radiation field quality was minimal. Thus one might expect some differences between present and earlier results to the extent that beam quality was influential.

It should also be noted in this connection that the energy of the neutrons emitted in the 0° direction from ~ 200 keV deuterons incident on tritium is 14.8 MeV, while the neutrons emitted at 90° have an energy of 14.1 MeV (De Pangher and Tochilin, 1969). For

the chamber geometry shown in Figs. 1 and 2 the neutrons are taken off at multiple angles and energies, and an approximate average energy of 14 MeV is assumed.

Collected charge for each chamber was measured for several applied voltages, averaged for both polarities, and linearly extrapolated to $1/V = 0$ on a $1/Q$ vs $1/V$ graph. This procedure thus corrected for saturation losses on the assumption of initial (columnar) ionic recombination.

The ratios of recombination-corrected charges collected from the various gases are shown in Fig. 3. The ratios for TE gas/air, (A150-1)/air, (A150-5)/air, (A150-1)/TE gas, (A150-5)/TE gas, and (A150-5)/(A150-1) are included, each plotted vs the mean chord length $\bar{\ell}$ in the various chambers ($\bar{\ell}$ was taken as 1 mm in the flat chamber). The precision of these charge ratios is estimated to be $\pm 2\%$ S.D.

Ratios of $\bar{W}$ values can be derived from ionization (Q) ratios according to the equation in the Appendix. Since that equation is based on the Bragg Gray relation, it might be expected to be most nearly valid for small cavities. Thus in each case we have extrapolated the data in Fig. 3 to zero chamber chord length $\bar{\ell}$. Q ratios thus obtained were employed in the equation, making use also of the relevant data in Table III to obtain the $\bar{W}$ ratios displayed in Table IV.

Table V contains $\bar{W}$ values for TE gas, A150-1 and A150-5 obtained by multiplying the corresponding $\bar{W}$ ratios in columns in 3-5 by $\bar{W} = 35.1$ eV/ion pr. obtained from the literature (ICRU, 1979) for dry air. Likewise, Table V includes $\bar{W}$ values for A150-1 and A150-5 gases derived in a similar way from $\bar{W}_{TE} = 31.1$ eV/ion pr. (Goodman and Coyne, 1980).

Fermilab Measurements

The Fermilab Cancer Therapy Facility generates a beam of fast neutrons by passing 66 MeV protons through a Be target 2.21 cm thick, which reduces the protons' energy by 49 MeV, after which they are stopped in a water-cooled Au plate. (Awschalom et al., 1979; Rosenberg and Awschalom, 1981). The resulting neutron spectrum emitted in the direction of the proton beam (0°) extends over the energy range 0-64 MeV, with an average around 25 MeV.

Measurements of relative ionization generated in the same set of ion chambers and the same gases (omitting Al50-5) were carried out in the Fermilab neutron beam to examine the effect of going to much higher neutron energies than 14 MeV. The ionization was measured with the microcomputer-controlled dosimetry system described elsewhere (Awschalom, et al. 1980). Three or four chambers were positioned in the beam simultaneously (with voltage connected and their collecting electrodes grounded), although charge from only one of them was measured at a time. Backscatter material (about 15 cm thickness of Al50 plastic) was provided just behind the chamber being measured in each case (see Fig. 4). Ionic recombination losses were corrected for as described with the UW-GTNS measurements.

Two different source-to-detector distances were used at the Fermilab (see Fig. 4). The flat 0.3 cm chamber, 1 cm³ #356RTG and the T8T6 8 cm³ chambers were measured at 190 cm SSD. To reduce the signal in the 80 cm³ chamber, it (together with the 193TG 1 cm³ chamber) was measured at about 350 cm from the target. At both positions the neutron beam was collimated to be slightly larger than 36 cm in diameter to cover the flat chamber and its scatterer. The current in the 80 cm³ chamber was still too

large to be measured with the microcomputer-based system, and a Keithley 616 electrometer with an external 4 1/2 digit voltmeter was substituted. In every case all comparable measurements with a given ion chamber were made with a single measuring apparatus and an undisturbed geometrical setup.

Collected charge was normalized to readings of a transmission-type monitor chamber located next to the target, and averaged for both polarities at each voltage.

In Fig. 5 are shown the ionization ratios for (Al50-1)/air, (Al50-1)/TE, and TE/air, for which the precision is estimated to be $\pm 1\%$ S.D. These data, extrapolated to small chamber size ($\bar{r} = 0$) and combined with appropriate data from Table III according to the formula in the Appendix gave the $\bar{W}$ ratio data in Table IV, for 25 MeV neutrons.

Table V contains values of $\bar{W}$ estimated by multiplying the $\bar{W}$ ratios in Table IV by the literature $\bar{W}$ values for air and TE gas cited in the footnotes of Table V. It should be noted that there are no $\bar{W}$ values available in the published literature specifically relevant to the Fermilab neutron spectrum, nor to a neutron energy of 25 MeV. We have therefore simply used the same reference $\bar{W}$ values as were used for the 14 MeV data, although their appropriateness is in doubt.

Discussion and Conclusions

First let us consider the 14 MeV neutron results in Table V.

Comparing TE gas with air and assuming $\bar{W}_{\text{air}} = 35.1$ eV/i.p. yields a value of $\bar{W}_{\text{TE}} = 30.6$ eV/i.p., 1.6% lower than Goodman and Coyne's value of 31.1 eV/i.p.

Al50 gas Mix 1 was found to have a $\bar{W}$ value of 27.2 eV/i.p. in comparison with air, or 27.6 eV/i.p. compared with TE gas, showing a 1.4% discrepancy between the two values.

$\bar{W}$ for the new Al50 gas Mix 5 was found to be $\sim 1\%$ higher than that for Al50-1: $\bar{W}_{\text{Al50-5}} = 27.5$ eV/i.p. relative to air, and 28.0 eV/i.p. relative to TE gas.

The results obtained at the Fermilab ($E_n \sim 25$ MeV) show somewhat different values for the $\bar{W}$ ratios in Table IV (hence also for $\bar{W}$ in Table V under the assumption of common values for the reference-gas $\bar{W}$'s) from those gotten at 14 MeV. $\bar{W}$ ratios for Fermilab data appear to be lower by 1.5% for (TE gas)/air and by 1.2% for (Al50-1)/air, while they are consequently higher for (Al50-1)/(TE gas) by 0.6%. These differences as a function of neutron energy are insignificant in view of the 1 2% S.D. of the data.

Comparisons may be made with some of the results reported earlier by DeLuca et al. (1980). Data in that experiment were processed in two ways: (a) all chambers averaged together, or (b) data extrapolated to zero chamber size. Those results are compared with present ones in the following tabulation for neutrons in the neighborhood of 14 MeV; ($\bar{W}$ in eV/ion pair):

<u>Author</u>	<u>Data Processing</u>	$\bar{W}_{TE}$ (vs. air)	$\bar{W}_{A150-1}$ (vs. air)	$\bar{W}_{A150-1}$ (vs. TE gas)
DeLuca et al. (1980)	Averaging	31.4	28.5	28.2
DeLuca et al. (1980)	Extrapolated	32.2	29.2	28.2
Present (~ 14 MeV)	Extrapolated	30.6	27.2	27.6

The least variation is shown by the data in the last column. Even so, the present ~ 14 MeV value of $\bar{W}_{A150-1} = 27.6$ eV/ion pr. is lower than that for the earlier measurements in the collimated 14.8 MeV neutron beam by 2.1%. This result may be significant inasmuch as we have been able even more recently to reproduce the earlier $\bar{W}$ measurements to within $\pm 1\%$. The admixture of many low-energy scattered neutrons in the present GTNS experiment is a possible cause of the observed difference.

Comparisons of ion chambers with calorimeters offers an absolute way of determining the product

$$\frac{\bar{W}}{e} \cdot \frac{(S/\rho)_w}{(S/\rho)_g} = \frac{D_w \cdot M_g}{Q}$$

Where $\bar{W}/e$ is given in J/C, D_w is the absorbed dose (J/kg) in the calorimeter medium (which may be Al50 plastic), M_g is the mass of gas (kg) in the ion chamber, and $Q(C)$ is the charge produced in that gas. This equation is a statement of the Bragg-Gray relation, hence small (non-perturbing) chambers are required. In case the gas is A-150 equivalent, $(S/\rho)_{wall}/(S/\rho)_{gas} = \text{unity}$, and $\bar{W}/e$ is thus directly obtained.

Such an experiment is under consideration here as the next logical step in studying Al50 gases as well as TE gas, with the Fermilab neutron beam and perhaps also the GTNS neutrons if the field strength is adequate for calorimetry.

References

- Anderson, H.H., and Zeigler, J.F., 1977. Hydrogen Stopping Powers and Ranges in all Elements. Pergamon Press, N.Y.
- Attix, F.H., Pearson, D.W., DeLuca, P.M. Jr., and Goetsch, S.J., 1980. Health Physics 38, 623.
- Awschalom, M., and Attix, F.H., 1980, Al50 plastic-equivalent gas. DOE Progress Rept. No. DOE/EV/01105-270 in WMP-121, and Phys. Med. Biol. 25, 567.
- Awschalom, M., Goodwin, R., Grumboski, L., Rosenberg, I., and Shea, M., 1980, High precision in dose delivery; routine use of a micro-computer. IAEA-SM-249/23, Fermilab, Batavia, IL 60510.
- Awschalom, M., Grumboski, L., Hrejsa, A.F., Lee, G.M., and Rosenberg, I., 1979. IEEE Trans. Nucl. Sci. NS-26, 3068.
- Caswell, R.S., Coyne, J.J., and Randolph, M.L., 1980, Rad. Res. 83, 217.
- DeLuca, P.M. Jr., Attix, F.H., Pearson, D.W., and Awschalom, M., 1980, Application of Al50 plastic-equivalent gas in Al50 plastic ionization chambers for ^{60}Co γ rays and 14.8 MeV neutrons. DOE Progress Report No. DOE/EV/01105-271 in WMP-121.
- DeLuca, P.M., Jr., Torti, R.P., Chenevert, G.M., Detorie, N.A., Tesmer, J.R., and Kelsey, C.A., 1978. Phys. Med. Biol. 23, 555.
- DePangher, J., and Tochilin, E., 1969. Chapter 23 in Vol. III of Radiation Dosimetry, Ed. by F. H. Attix and E. Tochilin, Academic Press, N.Y.
- Domen, S.R., 1980, Phys. Med. Biol. 25, 93.
- Goodman, L.J., and Coyne, J.J., 1980. W_n for Methane-Based Tissue-Equivalent Gas. Proc. of Workshop on Ion Chambers for Neutron Dosimetry, Rijswijk, The Netherlands, Radiobiol. Institute TNO.
- ICRU Report 31, 1979, ICRU Publications, P.O. Box 30165, Washington, D.C. 20014.
- Rosenberg, I., and Awschalom, M., 1981. Med. Physics 8, 99.

Table I

Compositions (by weight %) of the Gases Studied

	<u>TE Gas</u>	<u>Al50-Mix 1</u>	<u>Al50-Mix 5</u>
Methane (CH ₄)	39.7	--	--
Ethylene (C ₂ H ₄)	--	44.5	41.5
Propadiene (C ₃ H ₄)	--	37.8	42.1
Carbon Monoxide (CO)	--	10.3	--
Carbon Dioxide (CO ₂)	56.4	--	12.4
Nitrogen (N ₂)	3.9	3.6	3.6
Argon (Ar)	--	1.8	0.4
Freon 14 (CF ₄)	--	2.0	--
TOTAL	<u>100.0</u>	<u>100.0</u>	<u>100.0</u>

Table II

Elemental Components (by weight %) of the Gases Studied

<u>Component Element</u>	<u>TE Gas</u>	<u>Al50-Mix 1</u>	<u>Al50-Mix 5</u>
H	10.0	10.2	10.2
C	45.1	76.8	76.8
O	41.0	5.9	9.04
N	3.9	3.6	3.6
F	--	1.7	--
Ar	--	1.8	0.36
Total	<u>100.0</u>	<u>100.0</u>	<u>100.00</u>

Table III

Summary of Densities, Stopping Powers, and Kerma Factors

<u>Medium</u>	<u>Density</u>	<u>Stopping Powers</u> ³		<u>Kerma Factors</u> ⁴	
		<u>14 MeV neuts</u>	<u>25 MeV neuts</u>	<u>14 MeV neuts</u>	<u>25 MeV neuts</u>
Air	1.2929 ¹	100.5	68.2	2.29×10^{-9}	3.48×10^{-9}
TE gas	1.1493 ¹	119.2	80.2	6.58×10^{-9}	7.87×10^{-9}
Al50 gas, Mix 1	1.4423 ¹	120.8	81.1	6.72×10^{-9}	8.48×10^{-9}
Al50 gas, Mix 5	1.5176 ¹	121.3	81.5	6.75×10^{-9}	8.52×10^{-9}
Al50 plastic	1.126 ²	120.9	81.2	6.75×10^{-9}	8.52×10^{-9}

¹ In units of g/l for gases, at 0°C, 760 torr. Calculated by assuming ideal gases.

² After Domen (1980).

³ Mass collision stopping powers from Anderson and Zeigler (1977). In units of $\text{MeV cm}^2\text{g}^{-1}$, evaluated at an approximate mean proton energy (under charged particle equilibrium) of 3 MeV for 14 MeV neutrons, and 5 MeV for 25 MeV neutrons.

⁴ After Caswell et al., 1980. Given in units of $\text{rad per neutron/cm}^2$.

Table IV

Summary of $\bar{W}$ Ratios[†]

<u>Irradiation Facility</u>	<u>Approx. Neutron Mean Energy</u>	$\frac{\bar{W}_{TE}}{\bar{W}_{air}}$	$\frac{\bar{W}_{A150-1}}{\bar{W}_{air}}$	$\frac{\bar{W}_{A150-5}}{\bar{W}_{air}}$	$\frac{\bar{W}_{A150-1}}{\bar{W}_{TE}}$	$\frac{\bar{W}_{A150-5}}{\bar{W}_{TE}}$
UW-GTNS	14 MeV	0.871	0.774	0.784	0.881	0.901
Fermilab	25	.858	.765	*	.823	*

* A150-5 gas not measured at Fermilab

[†] Based on ionization ratios in Figs. 3 and 5 extrapolated to $\bar{x} = 0$.

Table V

Summary of $\bar{W}$ Values (eV/ion pair)

<u>Irradiation Facility</u>	<u>Approx. Neutron Mean Energy</u>	$\bar{W}_{TE}$	$\bar{W}_{A150-1}$	$\bar{W}_{A150-5}$	$\bar{W}_{A150-1}$	$\bar{W}_{A150-5}$
		(vs air) ¹	(vs air) ¹	(vs air) ¹	(vs TE) ²	(vs TE) ²
UW-GTNS	14 MeV	30.6	27.2	27.5	27.6	28.0
Fermilab	25 MeV	30.3	26.9 ³	--	27.8	--

The following footnotes give $\bar{W}$ values for air and TE gas from the literature, which were multiplied by the appropriate $\bar{W}$ ratios from Table IV to obtain $\bar{W}_{TE}$, $\bar{W}_{A150-1}$, and $\bar{W}_{A150-5}$.

¹ $\bar{W}_{dry\ air}$ for 5-MeV α particles and 1.8 MeV protons = 35.1 eV/i.p. (ICRU, 1979).

² $\bar{W}_{TE}$ for 14 MeV neutrons = 31.1 eV/i.p. (Goodman and Coyne, 1980).

³ Note that these $\bar{W}$ values were arbitrarily based upon the same reference $\bar{W}$ data (in footnotes 1 and 2) as were used with 14 MeV neutrons, for lack of more relevant $\bar{W}$ data for $\sim$ 25 MeV neutrons.

Fig. 1 Schematic plan view of the GTNS showing "close-in" ion chamber placement.

Fig. 2 Vertical section through target axis on the GTNS showing "close-in" ion chamber placement.

Fig. 3 Ionization ratios for $\bar{E}_n \approx 14$ MeV neutrons at the GTNS.

Fig. 4 Irradiation geometry employed at the Fermilab. The neutron beam was collimated to fully cover the 36 cm diameter flat chamber at each distance. 10 cm of Al50 plastic was placed behind the flat chamber for scattering. The other ion chambers were placed just in front of the flat chamber, but not shadowing its collecting volume.

Fig. 5 Ionization ratios for $\bar{E}_n \approx 25$ MeV neutrons at the Fermilab.

Appendix

It has been shown by Attix et al. (1980) in defining the First Corollary to the Bragg-Gray Relation that the ratio of $\bar{W}$ values for two gases g_1 and g_2 identically irradiated in the same Bragg-Gray cavity chamber is given to a close approximation by:

$$\frac{\bar{W}_{g_1}}{\bar{W}_{g_2}} \approx \frac{(\overline{S/\rho})_{g_1}}{(\overline{S/\rho})_{g_2}} \cdot \frac{\rho_{g_1}}{\rho_{g_2}} \cdot \frac{Q_{g_2}}{Q_{g_1}}$$

where $\bar{W}$ is the mean energy spent by the secondary charged particles in producing an ion pair in the cavity gas, $(\overline{S/\rho})$ is the mean mass collision stopping power for the charged particles traversing the cavity, ρ is gas density, and Q is the charge produced in the cavity gas.