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# *Personnel Dosimetry*

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PERSONNEL DOSIMETRY

(Lecture #4 by Herb Attix at the College on Medical Physics, ICTP, Trieste, September 4, 1992)

INTRODUCTION

The subject of personnel dosimetry is complex, involving not only the characteristics of the dosimeters themselves, but also how their readings should be interpreted in terms of the quantities they are intended to measure when worn on the body, for the types of radiation to be encountered - photons, neutrons and beta rays.

Two recent reports by the International Commission on Radiation Units and Measurements (ICRU) have provided useful relevant information:

- ICRU Report 43 (1988) - Determination of Dose Equivalents from External Radiation Sources (Part 2).
- ICRU Report 47 (1992) - Measurement of Dose Equivalents from External Photon and Electron Radiations.

This lecture will briefly summarize the recommendations of these reports, in relation to practical personnel dosimetry. Two definitions relating to area monitoring will be included also for clarity.

SUMMARY OF REPORT RECOMMENDATIONS

1. The dose equivalent, H, is defined as the product

$$H = \overline{Q}\, D$$

where $\overline{Q}$ is the effective quality factor, and D is the absorbed dose. All three quantities are specified at the same point of interest. [Note that a factor N, included in previous definitions of H, with an assigned value of unity, has been eliminated.]



2. $\overline{Q}$ is the dose-weighted average value of Q(L):

$$\overline{Q} = (1/D) \int Q(L) D(L)\, dL$$

where Q(L) is Q as a function of the unrestricted LET and D(L) is the spectrum of absorbed dose in unrestricted LET. [Note that the recommendation of the Joint Task Group in ICRU Report 40 (1986) that the lineal energy, y, be substituted for LET in this integration was not adopted by ICRU Report 43, and was not dealt with in ICRU #47.]

The currently accepted function Q(L) is shown in the following figure (Fig.2.3 from Attix text).

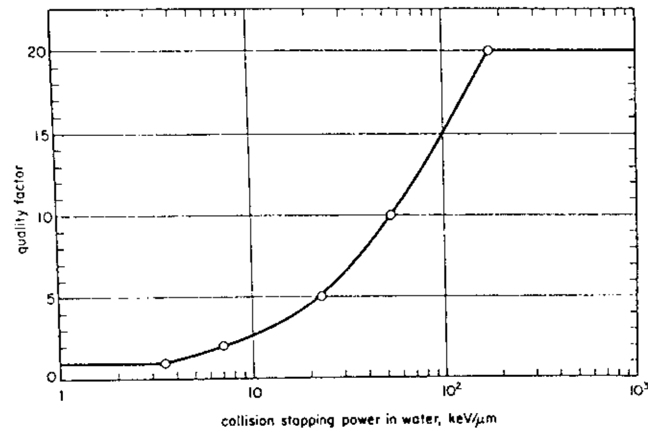



FIGURE 2.3. Quality factor Q of charged particles as a function of collision stopping power ($L_\infty$) in water, as recommended by the ICRP (1971). (Reproduced with permission from Pergamon Press, Ltd.)

For most purposes in radiation protection Q (and its average value) is taken as 1 for photons and electrons and 20 for neutrons. [A change of this latter figure to 25 was recommended in ICRU Report 40, but according to ICRU #43: "Since there has been no final action on the subject of Q, the present report does not reflect such changes."]

3. There are three operational quantities that have been defined for use in radiation protection practice, and are supposed to be measurable with monitoring instruments. Two of them are for area monitoring: ambient dose equivalent $H^*(d)$, and directional dose equivalent $H'(d,alpha)$. The third is for individual monitoring: personal dose equivalent $H_p(d,alpha)$.

4. Ambient dose equivalent, $H^*(d)$, at a point in a radiation field is the dose equivalent that would be produced by the corresponding "expanded and aligned" field in the ICRU sphere at depth d on the radius opposing the field direction, where:

a. d is taken as 10 mm for "penetrating" radiation, including photons above 15 keV and neutrons; d = 0.07 mm for weakly penetrating radiation, including photons below 15 keV and (more importantly) beta rays.

b. The ICRU sphere is tissue-equivalent, 30 cm in diameter, and of density 1 g/cm$^3$.

c. An "expanded" field has the same characteristics as that at the point of interest, but is large enough to cover the ICRU sphere. An "aligned" field has the same characteristics as that at the point of interest, except that it is unidirectional.

d. Units: Sv or J/kg.

e. The ideal instrument for measurement of $H^*(10)$ must have isotropic response. This means it cannot include the ICRU phantom, even though the definition requires it.



f. The ideal photon energy-dependence function for an area monitor that is calibrated in terms of $H^*(10)$ is shown in the following figure (Fig.3.1, ICRU #47), in which the maximum response per unit exposure at 60 keV simulates the effect of photon scattering from the ICRU sphere in the definition of $H^*(10)$. The shape of this curve can be roughly simulated in the design of practical area-monitoring instruments by selection of detector materials and wall thicknesses on the basis of their photoelectric effect and attenuation.

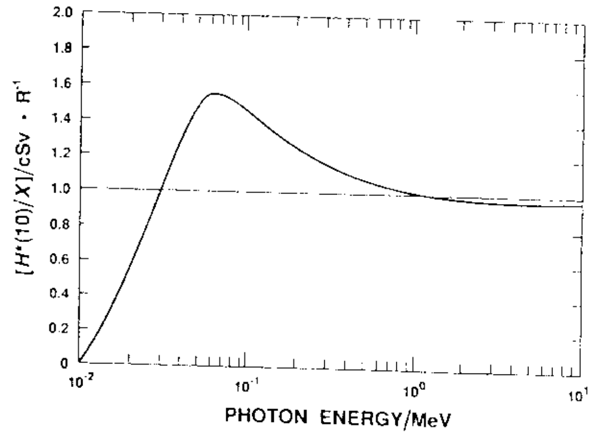



**Fig. 3.1.** The ambient dose equivalent, $H^*(10)$, per unit exposure, $X$, as a function of photon energy. The exposure is that obtained without the ICRU sphere in place (ICRU, 1985).

g. Area monitors for photons above 15 keV should be calibrated in terms of the ambient dose equivalent $H^*(10)$ [but in terms of directional dose equivalent (see Section 5) for beta rays]. Such a calibration is based on a conventional air-kerma or exposure calibration of the instrument, for example in free space (no phantom) in a Co-60 gamma-ray beam. The calibration factor is $N = H^*(10)/M$, where M is the instrument reading and $H^*(10) = 1.16K_a$ Sv for an air kerma of $K_a$ Gy, or $H^*(10) = 1.02X$ cSv for an exposure of X roentgens, assuming Co-60 gamma rays are used. [These conversion coefficients were taken from Table A.2 in ICRU #47.]

h. The ideal energy response function of a neutron area monitor that is calibrated in terms of $H^*(10)$ is shown in the following figure (Fig.4.2, ICRU #43). Actual neutron area monitors may differ substantially from this. A free-space calibration in terms of neutron fluence at some known energy can be converted to $H^*(10)$ by employing the corresponding point on this curve as a conversion coefficient.

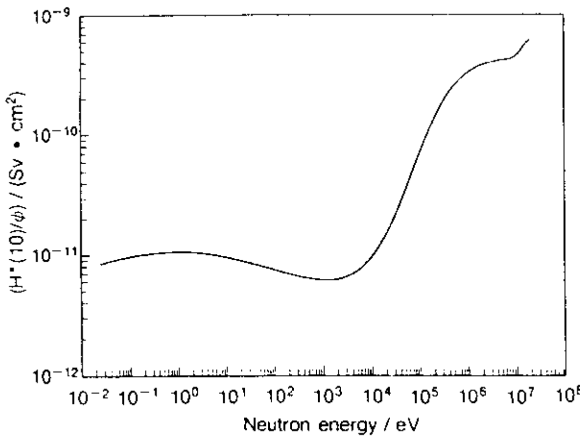



**Fig. 4.2.** Ambient dose equivalent, $H^*(10)$, per unit fluence, $\Phi$, for neutrons.



5. Directional dose equivalent, H'(d,alpha), at a point in a radiation field is the dose equivalent that would be produced by the corresponding "expanded" field in the ICRU sphere at a depth d on a radius in a specified direction.

a,b,c,d: same as in 4.

e. If the field is unidirectional, alpha is the angle between the specified direction and the radius opposing the field direction.

f. Since the value of H'(d,alpha) depends on the angle alpha, an instrument designed to measure it should have a similar angular response, instead of being isotropic.

g. Area monitors for beta rays should be calibrated in terms of the directional dose equivalent H'(0.07).

h. When alpha = 0, $H^*(d) = H'(d)$, as evident in the following figure (2.1 from ICRU#47):

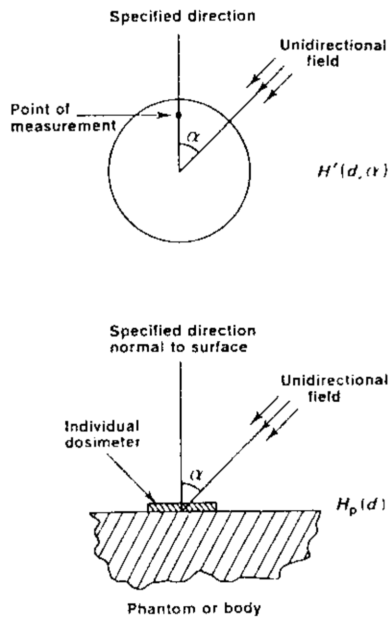



Fig 2.1. Definition of the angle α for $H'(d,\alpha)$ and $H_p(d)$.

6. Personal dose equivalent, $H_p$(d,alpha), is the dose equivalent in soft tissue at an appropriate depth d below a specified point on the body surface, resulting from radiation incident at angle alpha relative to the perpendicular to the body's surface, (see above figure).

a. For strongly penetrating radiation, d = 10 mm of unit density soft tissue; for weakly penetrating radiation, d = 0.07 mm relevant to skin, or 3 mm for the eye.

b. Practical measurement of $H_p$(d,alpha) can be done with a thin dosimeter that is worn at the specified point on the surface of the boay, and is covered with thickness d of tissue-equivalent material.

c. The dosimeter (with its d-thickness cover) is to be calibrated while fastened on the square face of a 30cm X 30cm X 15cm PMMA phantom, with the appropriate radiation incident perpendicularly (alpha = 0). For photons the following table (A.4, ICRU #47) relates $H_p$(10) on such a phantom to the free-space air kerma, which is assumed known at the point of measurement. The calibration factor is then N = $H_p$(10)/M, where M is the dosimeter reading.

TABLE A.4 - *Conversion coefficients relating $H_p(10)$ for a slab phantom of ICRU tissue, 30 cm x 30 cm x 15 cm, and air kerma, $K_a$. The 15-cm dimension is in the direction of the radiation (Grosswendt, 1991). (Data for non-normal photon incidence are given in Figure A.5.)*

| Photon Energy keV | $H_p(10)/K_a$ Sv Gy$^{-1}$ | Photon Energy keV | $H_p(10)/K_a$ Sv Gy$^{-1}$ |
|---|---|---|---|
| 10 | 0.0097 | 150 | 1.600 |
| 15 | 0.268 | 200 | 1.489 |
| 20 | 0.613 | 300 | 1.370 |
| 25 | 0.879 | 400 | 1.301 |
| 30 | 1.105 | 500 | 1.256 |
| 40 | 1.495 | 600 | 1.230 |
| 50 | 1.769 | 800 | 1.191 |
| 60 | 1.890 | 1000 | 1.175 |
| 80 | 1.891 | 1500 | 1.140 |
| 100 | 1.8[illegible] | | |



d. The ideal personnel dosimeter for penetrating photons has the angular-dependent response sh[illegible]n in the following figure (A.2, ICRU #47). It is assumed [illegible]at the ratio H'(10,alpha)/$H^*$(10) [or /H'(10)] is the same as $H_p$(10,alpha)/$H_p$(10), i.e., that the body is adequately approximated by the ICRU sphere.

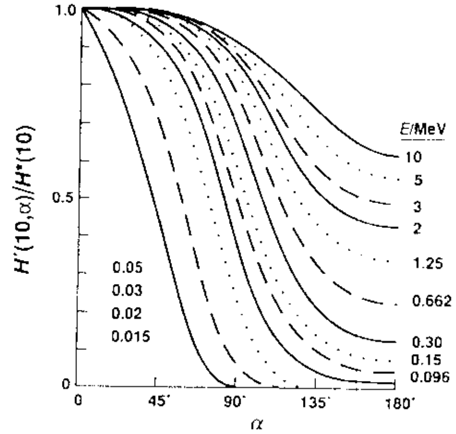



Fig. A.2. Variation of the quotient $H'(10,\alpha)/H^*(10)$ with angle of incidence, α, for monoenergetic photons of various incident energies (Grosswendt and Hohlfeld, 1982).

e. For neutrons perpendicularly incident on the body (or the 30x30x15 cm PMMA phantom), the energy dependence of an ideal dosimeter should follow the $H_p$(10) response curve, which is assumed to be the same as $H^*$(10), shown before (Fig.3.1, ICRU #47). There are as yet no formal recommendations regarding angular dependence of $H_p$(10,alpha) for neutrons.

f. For beta rays, since Q is taken as unity, the ideal dosimeter for measuring $H_p$(0.07, alpha) responds in proportion to the absorbed dose in tissue at a depth of 7 mg/cm$^2$. The desired dependence on angle of beta-ray incidence is shown in the following figure (Fig.A.4, ICRU #47):

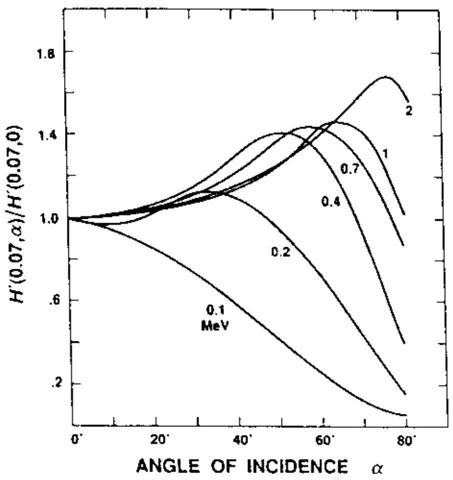



Fig. A.4. Relative variation of directional dose equivalent $H'(0.07,\alpha)$ with angle of incidence, $\alpha$, for a given fluence of monoenergetic electrons. The numbers on the curves give the electron energies in MeV (Cross, 1988).

7. Effective dose equivalent, $H_E$, is the weighted average of the dose equivalents ($H_T$) in certain organs or tissues of the body, each weighted by an organ weighting factor, $w_T$; thus:

$$H_E = \sum_T w_T H_T$$

The $w_T$ values were chosen by the ICRP to reflect the relative risk of death from cancer or occurrence of severe hereditary effects in the first generations after uniform whole-body exposure. Currently recommended values of $w_T$ are shown in the following table (p.20 in ICRU #43):



| Tissue | $w_T$ |
|---|---|
| Gonads | 0.25 |
| Breast | 0.15 |
| Red bone marrow | 0.12 |
| Lung | 0.12 |
| Thyroid | 0.03 |
| Bone surfaces | 0.03 |
| Remainder | 0.30 |

Each of the five "remainder" organs receiving the highest dose equivalents are assigned $w_T$ = 0.06. When the GI tract is irradiated, the stomach, small intestine, upper large intestine and lower large intestine are counted as four separate remainder organs.

a. The relationship of the effective dose equivalent to the personal dose equivalent for penetrating whole-body photon irradiation is shown in the following graph of $H_E/H_p(10)$ vs photon energy (Fig.5.4, ICRU #43). So long as the dosimeter is not worn on the opposite side of the body from an incident monodirectional beam, and is calibrated in terms of $H_p(10)$, the effective dose equivalent is seen to be adequately approximated. The over-estimate below 100 keV is regarded as acceptable.

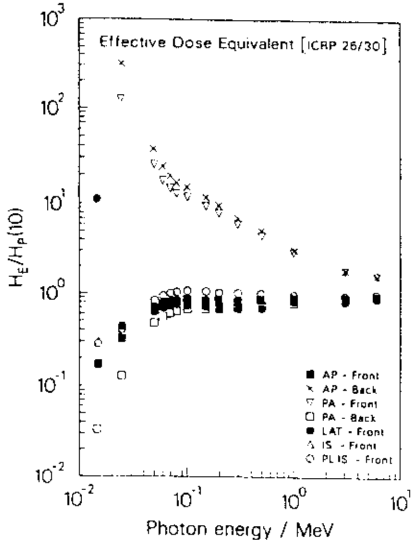



**Fig. 5.4.** Ra... of the effective dose equivalent, $H_E$, to the individual dose equivalent, penetrating, $H_p(10)$, as a function of photon energy. Two locations for the personal dosimeter are considered: front of the body (Front) and back of the body (Back). $H_p(10)$ is approximated by the dose equivalent at depth 10 mm along the central axis in the ICRU sphere (see text) (ICRP, 1977, 1979). Five geometries are considered in the calculations: AP, broad parallel beam from front to back (anterior-posterior); PA, broad parallel beam from back to front (posterior-anterior); LAT, broad parallel beam from the side (lateral); IS, isotropic field; PL.IS., planar isotropic field, perpendicular to body axis.

b. The relationship of the effective dose equivalent to the personal dose equivalent for penetrating whole-body neutron irradiation is shown in the following graph of $H_E/H_p(10)$ vs neutron energy (Fig.5.12, ICRU #43). For all the beam directions and energies shown $H_p(10)$ overestimates $H_E$. The ratio rises toward unity above 0.1 MeV.



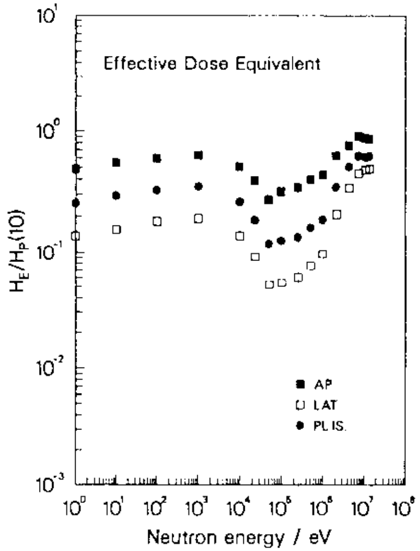



**Fig. 5.12.** Ratio of the effective dose equivalent, $H_E$, to the individual dose equivalent, penetrating, $H_p(10)$, as a function of neutron energy. The personal dosimeter is considered to be worn on the front of the body. $H_p(10)$ is approximated by the dose equivalent at depth 10 mm in the ICRU sphere. Three geometries are considered in the calculations: AP, broad parallel beam from front to back (anterior-posterior); LAT, broad parallel beam from the side (lateral); PL.IS., planar isotropic field, perpendicular to body axis.

c. For beta rays incident on the surface of the body where the personal dosimeter is worn, an ideal dosimeter calibrated in terms of personal dose equivalent $H_p(0.07)$ will give a direct measure of dose equivalent to the basal layer cells in the exposed skin.

# PRACTICAL PERSONNEL DOSIMETERS

## Dosimeters for Strongly Penetrating Photons

Low-Z thermoluminescent dosimeters (TLDs) such as LiF(Mg,Ti) are probably the detector of choice for this application. They are commercially available from several sources, along with the necessary readout equipment, and have been widely used for many years. Their response per unit exposure is flat enough so that, when the TLD is worn on the body or attached to a phantom, the photon energy dependence approximates that of $H_p(10)$ [see above Table A.4]. ICRU #47 cites, for example, Bartlett et al (Rad.Prot.Dosim. 17, 29,1986), who reported that the measured response to normally incident photons of LiF-Teflon dosimeters 20 mg/cm$^2$ thick under a 0.7 g/cm$^2$ plastic layer was flat within +/- 15% relative to H'(10) [or $H_p(10)$] from 40 keV to 1.25 MeV(Co-60). And because TLDs are usually planar in configuration, their angular dependence (when mounted behind the correct thickness of tissue-equivalent material) is approximately proportional to $H_p$(10,alpha), as defined in Fig.A.5, above.

Li$^7$F has the further advantage for personnel dosimetry of being insensitive to neutrons, except for responding to the n,gamma photons generated from thermal neutron capture by hydrogen atoms in the body. Thus it can be used in conjunction with a neutron dosimeter to measure the $H_p(10)$ for photons.

## Beta-Ray Personnel Dosimeters

The same TLDs that are useful for strongly penetrating photons are applicable as well for beta ray dosimetry, except that $H_p(0.07)$ is the quantity to be measured. The sensitive layer of TLD must be very thin to give the desired response function vs energy and angle. A thickness of 2 mg/cm$^2$ of TLD phosphor under a 7 mg/cm$^2$ plastic layer is reported to be satisfactory (ICRU #47).



## Neutron Personnel Dosimeters

### a. Albedo type TLDs

The most common neutron personnel dosimeters are TLDs that respond to the neutrons that are thermalized by the body, and diffuse out to strike the dosimeter. Li$^6$F, which is sensitive to thermal neutrons through the $^6$Li(n,alpha)$^3$H reaction. [This is called an "albedo" dosimeter, since albedo is a synonym for reflectance.]

Such dosimeters have an energy response function that decreases with increasing incident neutron energy, as shown in the following graph of neutron albedo (Fig.16.14 in Attix text), instead of increasing like the $H^*(10)$ curve in Fig.4.2 from ICRU #43 shown previously.

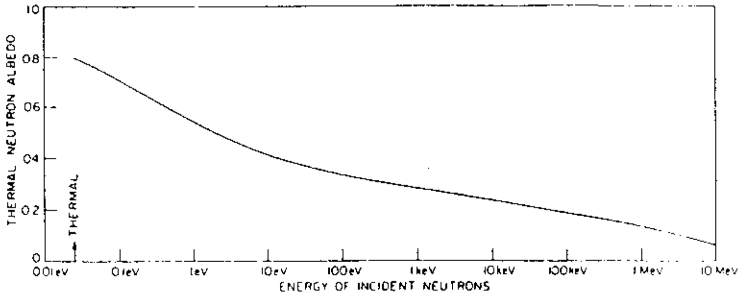



**FIGURE 16.14.** Thermal-neutron albedo from the human body, as a function of the energy of perpendicularly incident neutrons. (Harvey, 1967. Reproduced with permission from J. R. Harvey, Berkeley Nuclear Laboratories, U.K.)

Such a dosimeter thus does not measure personal dose equivalent $H_p(10)$ for neutrons of energies other than the single energy (or spectrum) for which the dosimeter is calibrated on a phantom. Commonly the calibration is done with a fission spectrum (avg. energy of 2 MeV), thus accepting an over-response to neutrons that have been degraded to lower energies.

b. CR-39 Etch-Track:

Thin layers of CR-39 plastic are sensitive to local damage along the tracks of the recoil protons resulting from neutron collisions with H atoms in the CR-39 or in an overlying layer of other hydrogen-rich plastic, e.g., polyethylene. The latent damage must be "developed" by chemical or electrochemical etching to make the tracks visible with magnification, so they can be counted. Neutrons between about 30 keV and 4 MeV are detectable. At lower energies the tracks are too short; at higher energies the LET is too low to do enough damage to be developable. A thicker overlayer can be employed to decrease the proton energy to the detectable range.

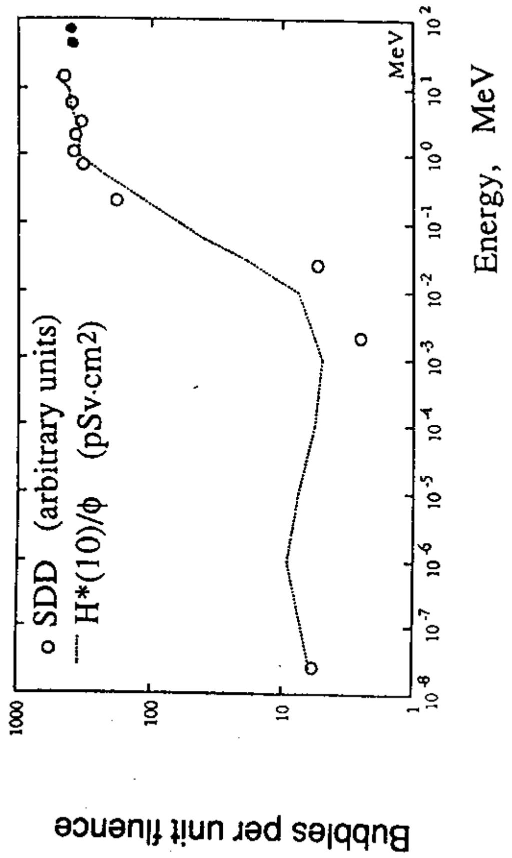
Although this dosimeter cannot be said to measure $H_p(10)$ over a range of neutron energies, it can be calibrated to measure this quantity for a single energy or spectrum of fast neutrons. For example, CR-39 with a 1-mm overlayer of polyethylene has a typical sensitivity to an AmBe neutron spectrum (avg. energy 4.4 MeV) of 2.3 tracks per microSievert (or 23 tracks/mrem).

c. Apfel Neutrometer:

This commercial dosimeter is somewhat large (16 cm tall X 14 mm diameter, 10 g.) to be regarded as a personnel dosimeter, but its energy dependence is unique in tracking the $H_p(10)$ function over the full range of neutron energies, according to data supplied by Apfel:

15-6

ENERGY RESPONSE OF SDD-100 MATERIAL




Solid dots represent preliminary data at 46 and 66 MeV taken at Paul Scheer Institute provided by Francesco d'Errico of the University of Pisa.



The bottom half of the Neutrometer is filled with a gel containing microscopic superheated liquid droplets. When a secondary charged particle from a neutron interaction strikes one of these droplets, it changes into a small gas bubble. The increase in volume causes a piston carrying an indicator to move up a scale in the upper half of the device, which is calibrated in terms of $H_p(10)$, from 5 to 1000 mrem (0.05 - 10 mSv). The bubbles are large enough to be visible, and can be counted for greater sensitivity: 7 bubbles = 1 mrem = 0.01 mSv. The device can be worn for up to a month, or until its reading goes off-scale.

CONCLUSIONS

The system of quantities and units that has been developed by the ICRU over many years for handling radiation protection measurements remains quite complex, even after the recent definition of "operational quantities" that are intended to simplify the situation.

Practical dosimeters for measuring personal dose equivalent are quite satisfactory for strongly penetrating photons. For beta rays only the thinnest possible TLDs will suffice for measuring $H_p(0.07)$. For neutrons the challenge of a convenient sized personnel dosimeter that can measure $H_p(10)$ over a wide range of energies remains to be solved, although the Apfel device seems to come closest so far.