Recent Deaths

Benjamin S. Paschall, 67, formerly professor of chemistry at Washington State University and for the past seven years president and head chemist of the Paschall Laboratories, Seattle, died on 22 November.

Frederick B. Mumford, 78, dean emeritus of the College of Agriculture, University of Missouri, died on 12 November, as the result of an automobile accident in which Mrs. Mumford also lost her life. He had been dean of the College of Agriculture from 1909 to 1938 and dean emeritus since the latter date.

Charles Needham Forrest, 70, retired chemical engineer formerly with the Barber Asphalt Corporation of Perth Amboy, New Jersey, died in Fort Myers, Florida, on 2 December.

James Henry Leuba, 78, professor emeritus of psychology at Bryn Mawr, died at Winter Park, Florida, on 8 December. Among Dr. Leuba's books are: *The psychological origin and the nature of religion, A psychological study of religion, The belief in God and immortality,* and *The psychology of religious mysticism.*

Henry A. Trautman, 54, head of the Trautman Chemical Engineering Company, Cleveland, died on 3 December.

In the Laboratory

Photographic Measurement of Radiation Quality and Quantity

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It is recognized authoritatively that the degree of ionization produced by X-rays is a relative measurement of quantum energy, the intensity of which is expressed as the number of roentgens per unit time (*6*). For a beam of radiation having a given intensity, a quality index of the degree of ionization produced, or the amount of energy absorbed, in a unit mass is expressed as the relative absorption in various thicknesses of a material (usually full absorption curves in Cu or Al), a simplified value of which is the HVL (thickness of material that reduces the ionization to one half). The biologic effect is thus expressed as the exposure in roentgens (intensity × time) to radiation of a given tissue absorbability.

To date, the standard free-air ionization chamber has been accepted as the most accurate instrument for measurement of radiation quality and intensity. According to the definition of the roentgen, the only requirement of an X-ray measuring instrument is that it indicate the same number of r's per unit time as the standard air chamber when placed at the same point in a suitably defined beam (*11*). The principles of the free-air chamber have been recently extended to the development of the thimble-type chamber, the wall of which is of a material approximating human tissue in density and X-ray absorption. Its accuracy is dependent on calibration with the free-air chamber and the conditions under which it is used. Because extensive laboratory equipment is not required, this instrument is readily employed for the measurement of small doses of scattered and direct radiation in field studies.

The photographic effects of X-rays have been studied extensively as a basic science since their discovery in 1895. Most of these studies were based on the Bunsen and Roscoe reciprocity law, $E = It$ (*5*), and the Hurter and Driffield characteristic curve relating density and the logarithm of exposure (*10*), which had been reported previously for visible light. Barkla and Martyn (*1*) in 1913 concluded that the photographic effect produced by X-ray beams of a given intensity varied with the wave length—the more penetrating the radiation, the smaller the photographic effect. This was confirmed by Berthold and Glocker, Bouvers, and Bell (*2–4*). Bell also showed that, if development variables are eliminated and intensifying screens are not used, the shape of the H & D curve is independent of quality; under these conditions the failure of the reciprocity law was found to be negligible (10 per cent or less for an intensity range of 1–10,000). Bell and Henny (*2, 8*) found that, unless intensifying

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screens are used, the "intermittency effect" is also negligible. Preliminary work by the present authors confirmed these findings. It was concluded that, if a "characteristic curve" representative of the material and development employed is available for a specific quality of radiation, such a curve can be used to determine accurate relative intensities from film blackening when the densities corresponding to the film blackening and the "characteristic curve" are read on the same densitometer or on similarly calibrated instruments. Also, when the effect of quality on film blackening is known, such a curve may be used to determine accurate relative intensities of radiations of varying quality.

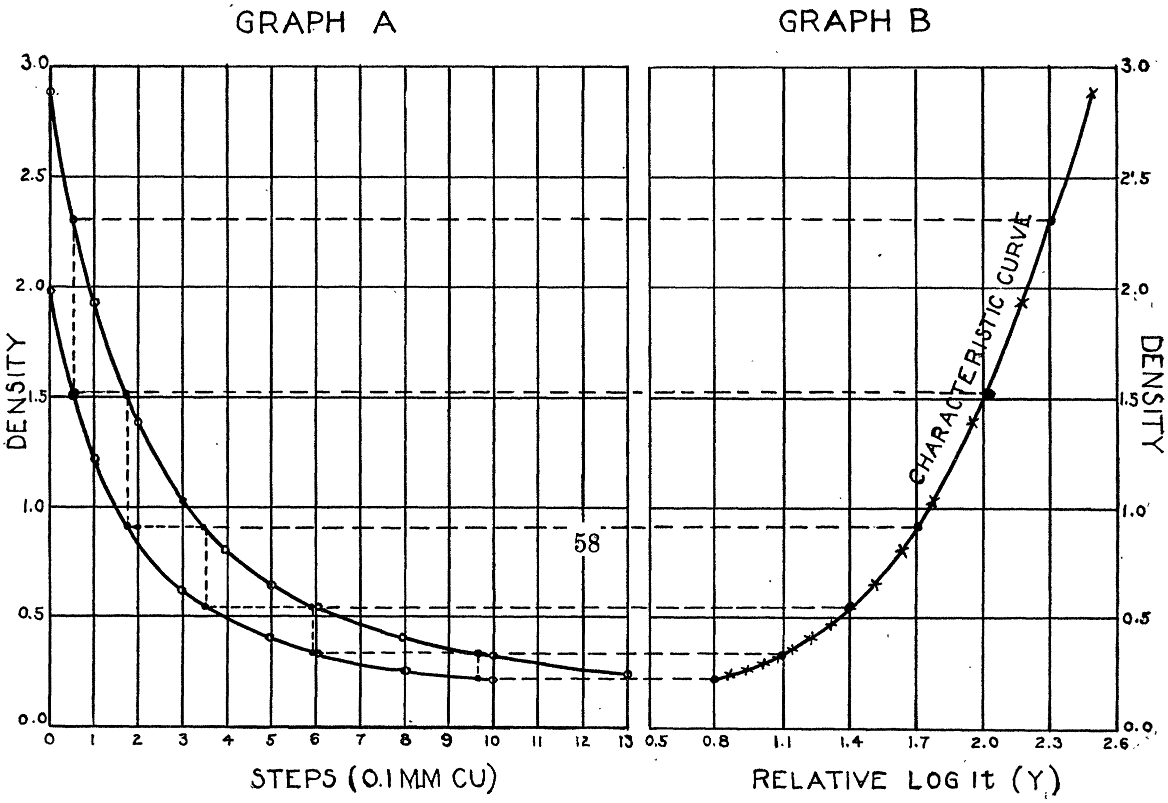

FIG. 1. *Graph A*—Densities obtained under step tablet: lower curve = average of densities produced by single exposure; upper curve = densities produced by cumulation of two exposures; ○ = densities obtained under various tablet steps; ● = construction points for characteristic curve; vertical dotted lines represent the density increment for 0.30 *log It* at the designated points. *Graph B*—● = construction points, placed on ordinates 0.30 *log It* apart, for characteristic curve, corresponding to similar points on the curves of Graph A and connected with them by interrupted lines to show the graphic construction employed. For convenience in graphing, a density of 1.5 and a *relative log It* of 2.0 were used as standard points of departure. × = densities produced under 0.1 mm. thickness of Cu varying from 0.0 to 1.3 mm. and corresponding to the *relative log It* values used for the construction of the photoabsorption curve (Fig. 2).

To date it has been difficult to duplicate the conditions under which a "characteristic curve" may be determined. For this reason intensity values derived from film blackening have not been sufficiently accurate for comparative measurement of radiation quality and quantity unless extensive laboratory control is applied. A vast amount of sensitometric data has accumulated through many researches, both from the point of view of general radiography (*9, 12*) and the use of films for radiation measurement (*2, 8*). These authors have shown that quantitative errors seldom exceed 5 per cent if films of the same type and emulsion number are developed simultaneously; however, a discrepancy up to 30 per cent was reported if the films are developed at different times, and this error may be increased to 50 per cent or greater if films of different emulsion numbers are used. These errors were found when the conditions of development were supposedly similar. Henny (*8*) has shown that films of the same emulsion number, developed for 6 instead of 5 minutes, may show an error as great as 100 per cent. The present authors found errors of similar magnitude in earlier experiments.

A simple method for determining the "characteristic curve" (v.s.) under routine conditions was developed from previous investigations by one of us (J.K.) for the photometric calibrations of X-ray equipment. The authors report herein the application of the principles of the method in the measurement of radiation quality and quantity in terms equivalent to presently accepted methods.

DETERMINATION OF A REPRESENTATIVE "CHARACTERISTIC CURVE"

A metal stair tablet is placed over the film (thickness 0 included), a lateral third of which is covered by a lead mask, and an exposure, *It* (I = intensity, t = time), in roentgens measured by a r-meter is made. The strip of lead is then removed and placed over the contralateral third of the film, and a duplicate exposure is made. Upon processing, the film thus furnishes a tablet image divided into three zones. The parts of the film covered with lead receive a single exposure, respectively, whereas the remaining middle third of the film receives both exposures. Thus, the latter zone receives an exposure equal to twice the average of the exposures received by the other zones. The exposures should be so chosen by trial or by known data that a maximum readable density is obtained on step 0 in the zone receiving both exposures. The resulting densities are plotted directly as density vs. filter thickness curves (Fig. 1, Graph A), the lower curve being equivalent to the average of the densities determined in that part of the film receiving a single exposure, and the upper curve representing the density determined in the part of the film receiving the two exposures. In employing the average of the densities obtained for single exposures, any difference in *It* caused by failure of the equipment to duplicate exposures exactly is minimized in graphing the curve. The authors have found that a difference in exposure up to 10 per cent usually does not result in a significant difference in the shape of the "characteristic curve." From these two curves points are determined, 0.30 *log It* apart corresponding to the density increment produced either by halving or doubling the exposure. A "characteristic curve," density vs. *relative log It,* is determined as shown in Fig. 1, Graph B. This curve is similar to an H & D (density vs. log time) curve, and is of the same shape, assuming no failure of the reciprocity law. It is characteristic of the material, developing process, and densitometer used. Cumulative errors involved in the determination of this curve were found to be small. Curves obtained from exposure of films of the same emulsion number to varying dosages and qualities of radiation were found to match within 0.02 *log It* within the range of densities between 0.30 and 3.0, a variation found to be within limits satisfactory for most practical purposes. It is thus possible to determine an unknown dosage, *x,* in r's from the film blackening produced by an X-ray beam of normal incidence and of the same quality as that employed in exposing the film used for the determination of the "characteristic curve" by the equation:

$$x = s\ [\text{antilog}\ (Y_x - Y_s)], \qquad (1)$$

wherein s is the dosage in roentgens given this film, and Y_x and Y_s are the *relative log It* values, corresponding to the film densities produced by x and s, respectively, as determined from the "characteristic curve" for the film and processing employed.

DETERMINATION OF QUALITY

An indication of the quality of radiation is derived from the "characteristic curve" in Fig. 1, Graph B, by plotting *relative log It* vs. filter thickness as shown by the curve in Fig. 2, thus resulting in a "photographic absorption curve" characteristic of the beam. Curves obtained by this method are a measure of variation in photographic effect only, and are not directly comparable with ionization absorption curves. It has been shown by Glasser (7), and confirmed in our experiments, that the relationship between photographic and ionization effects changes with the wave length. However, it is reasonable to assume that the two types of curves bear a definite relationship, and that they can be transposed from one type to the other when the ratio "photometric intensity/ionometric intensity" for given conditions is known.

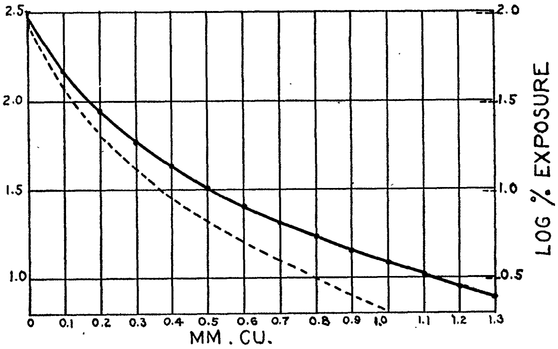

FIG. 2. ——— = photoabsorption curve obtained from data of Graphs A and B, Fig. 1. From such curves the photo half-value layer can be determined for any filtration as compared with the ionization HVL from conventional absorption curves: PQI is 0.110, and the photo HVL, 0.092. Curve obtained at approximately 100 KVP full-wave valve rectification, 1 mm. Al total filtration, using ultraspeed dental X-ray film. – – – – – – = photoabsorption curve of standard beam used in experiments, using ultraspeed dental X-ray film; PQI is 0.088, and the photo HVL, 0.068. The same curve was obtained with slow-speed dental film and slow-speed, fine-grain industrial film.

It was found that the slope of this quality curve might be expressed conveniently in an approximate half-value layer to which is applied the term "photographic quality index." This index is derived from the HVL formula, the thickness of filter in millimeters to reduce the intensity of a beam by one half, *i.e.* $\frac{I_0}{I_m} = 2$, where I_0 is the incident radiation intensity, and I_m is the intensity of the beam after passing through filter thickness, *m*. For monochromatic radiation following the law, $I = I_0e^{-nd}$, the HVL can be calculated from the equation:

$$\frac{m \log 2}{\log \frac{I_o}{I_m}} \quad \text{or} \quad \frac{0.30\ (m)}{\log I_o - \log I_m}. \tag{2}$$

Similarly, the quality of a beam is referred to by its photographic quality index:

$$\frac{m \log 2}{\log \frac{(\text{photointensity at o})}{(\text{photointensity at m})}} \quad \text{or} \quad \frac{0.30\ (m)}{Y_o - Y_m}, \tag{3}$$

where Y_o is the *relative log It* value for the density under step 0, *i.e.* without filtration, and Y_m the *relative log It* value for the density caused by the radiation after passing through *m* filter thickness. The straight-line function is thus assumed for heterogenous radiation. This assumption has been found valid for a first approximation of quality ranging from 60 to 250 KVP when *m* represents 0.2 mm. Cu. Under these conditions Equation (3) may be expressed as:

$$\frac{(0.2) \log 2}{Y_o - Y_{0.2\ \text{mm. Cu}}} = \frac{0.06}{Y_o - Y_{0.2\ \text{mm. Cu}}}. \tag{4}$$

It is felt that the value of this photographic quality index, designated PQI, is of the same order of significance as the HVL of an X-ray beam. It is derived from photographic effects, whereas the HVL, by definition, is obtained from intensities measured by ionization effects. It is recognized that the PQI per se, as is true with the HVL, does not furnish a complete description of quality. Two X-ray beams of the same PQI might, under certain conditions, vary markedly in quality; nevertheless, two other X-ray beams of the same PQI value are of approximately the same quality when the differences in filtration are not great. It may be added here that the photographic half-value layer, *i.e.* the filtration which reduces the photographic effect by one half, may be obtained from the photoabsorption curve (Fig. 2) or more directly from the curves in Fig. 1, Graph A. The procedure requires two controlled exposures and the graphing of the determinations of film blackening under a minimum of three steps, including steps 0, 0.1, and 0.2 mm. Cu. However, the PQI can be obtained by a single exposure involving the determination of film blackening produced under two steps, *i.e.* 0 and 0.2 mm. Cu, when the "representative characteristic curve" is known. This markedly simplifies the procedure when a number of measurements are to be made. The PQI has proved as satisfactory as the photographic half-value layer within the general accuracy obtained in dosage measurement by the method here presented.

DETERMINATION OF DOSAGE

An X-ray beam of a given quality will produce a given photographic effect. The resultant film blackening will depend on the type of film and the development conditions. Assuming no failure of the reciprocity law, if the beam quality is kept constant and the development conditions are controlled, film blackening is dependent only on exposure *It*. Under these conditions, the degree of film blackening produced by a known exposure in roentgens can be empirically determined. It is then possible to interpret film blackening as greater or less than a known exposure in roentgens. However, if the "characteristic curve" representative of the material and development conditions and the film blackening due to an exposure to a given dose in r are known, then it is possible to translate film blackening directly into roentgens by Equation (1). However, with beams of a different quality this value of *x* is no longer a direct expression of the dose in r, since the number of r's required to produce a given film blackening varies with quality.

For a beam of a given quality, *a*, the density produced by a known exposure in r is represented on the curve by *relative log It* (a) or Y_a. Similarly, for a beam of a different quality, *b*, the density produced by the same exposure in r is represented by *relative log It* (b) or Y_b. Since the "characteristic curve" is independent of quality, then $Y_a - Y_b$ represents the log of the ratio of the photographic effects, P_a and P_b, of the two beams, *i.e.*

$$\log \frac{P_a}{P_b} = Y_a - Y_b. \tag{5}$$

Thus, film blackening produced by an unknown dose from a beam of known quality, *b*, can be translated into r value upon comparison with the film blackening produced by a known dose in r of a beam of known but different quality, *a*. Equation (1) thus resolves itself into the following:

$$X_b = \frac{P_a}{P_b} S_a\ [\text{Antilog}\ (Y_{x_b} - Y_{s_a})], \tag{6}$$

where X_b is the unknown dosage of beam quality *b*, and S_a the known dosage of beam quality *a*.

When a beam of quality *a* is used as a standard, and the photographic effect, P_a, is considered as unity, then $\frac{P_a}{P_n} = \frac{1}{P_n}$, wherein P_n is the photographic effect of a beam of any quality. The values of $\frac{1}{P_n}$, when determined for beams of different quality in comparison with the standard beam, can be used as coefficients for quality *Cq*. The equation then becomes:

$$X = Cq\ (s)\ [\text{Antilog}\ (Y_x - Y_s)], \tag{7}$$

where *Cq* is the proper coefficient for the quality of the beam used for the unknown exposure, and *s* is the value in r of the exposure made with the beam of standard quality.

The authors have determined the *Cq* for beams of various qualities expressed in PQI, using a standard beam (80 KVP, fully rectified, 1 mm. Al total filtration, and a PQI value of 0.088). *Cq* for PQI values ranging from 0.060 to 0.300 are shown in Fig. 3. The graph is only a first approximation; these values will probably require correction dependent on additional experimental work with varying KVP and filtration. Employing the *Cq* values derived from this graph as correction factors in Equation (7), the authors tested the accuracy of the photographic method by simultaneous exposure of film and a thimble-ionization chamber (condenser r-meter). Direct radiation at a right angle to the film, varying in kilovoltage from 60–250 KVP and in dosage from 0.05–5.0 r, was used for this purpose. In a series of 53 observations to date the mean of the difference in r values between the ionization and photographic measurements as obtained in individual tests was 5.6 ± 1.2 (S. D. of the mean) per cent.

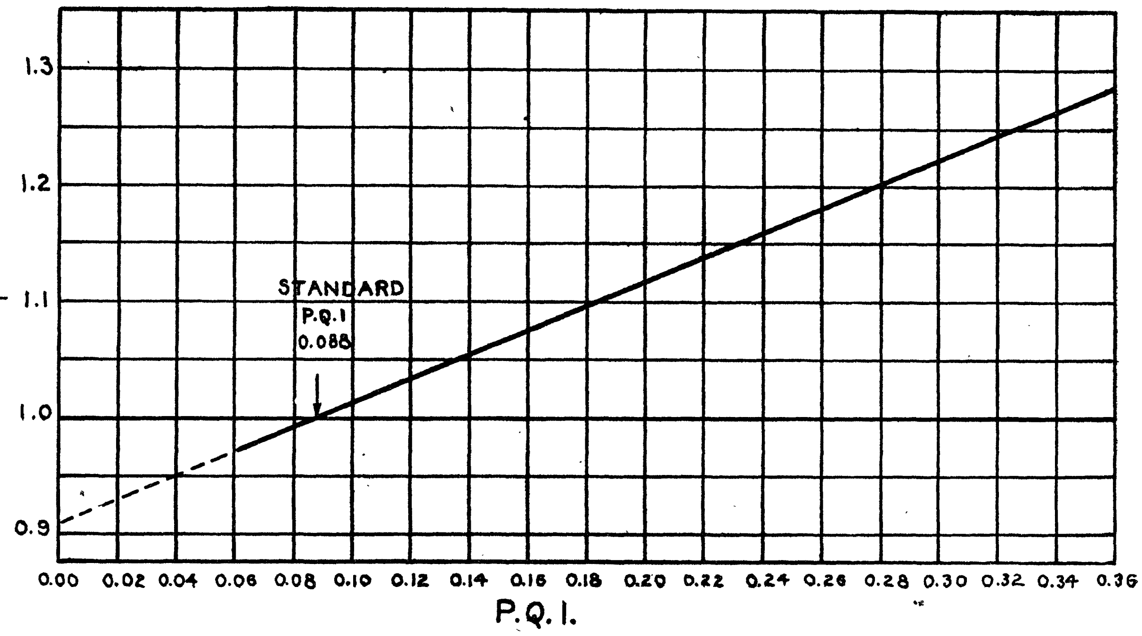

FIG. 3. Relation of correction coefficient for quality *Cq* and photoquality index, PQI, for determination of dosage from film blackening; actual values shown in graph are those for a standard beam of 0.088 PQI; coefficient values for any other beam used as control can be found by using the ratio : $\frac{C_q \text{ for tested beam}}{C_q \text{ for control beam}}$; graph values approximate only, probably accurate within 5 per cent for PQI values from 0.06 to 0.36.

Preliminary work with both direct and scattered radiation at other than normal incidence indicates that a similar accuracy can probably be obtained under these conditions when experimentally determined correction factors for angle of incidence and scattering are used. Details of this work, and the practical application of the photographic method in personnel monitoring and X-ray machine calibration will be reported in a subsequent paper. The authors recognize that the ionization chamber affords the most accurate method for radiation dosage determination. The small number of trial tests (75 to date) made with the photographic method herein described do not permit thorough evaluation. However, the relative accuracy of the method is encouraging. It is felt that further investigation is warranted because of the simplicity, inexpensiveness, and convenience of the method. The method is particularly adaptable to the determination of exposure of personnel to radiation for prolonged periods, including the approximation of the quality of radiation received, the calibration of equipment with a minimum of test exposures, and the standardization of radiographic technics.

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