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Energy absorbed in calcium tungstate x-ray screens*

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The energy which must be absorbed in a $CaWO_4$ x-ray intensifying screen to produce unit net optical density on a film has been evaluated by measurement and calculation for a screen–film system over a range of beam qualities (1.4–7.4 mm Al HVL) spanning the diagnostic x-ray region. It was found to be constant within experimental error. The absorbed-energy constant for three additional $CaWO_4$ screens is presented for a single beam quality. To correct the estimation of absorbed energy, the fractional escape of tungsten K x rays has been evaluated and the results are presented as a function of phosphor loading. The absorbed-energy constant is useful for predicting optical density for variable beam conditions; a family of characteristic curves based on exposure is reduced to one curve for a particular film–screen system, expressed as optical density as a function of absorbed energy.

I. INTRODUCTION

In diagnostic radiology, the use of x-ray film-intensifying screen systems is widespread. X-ray energy is converted to light-photon energy by the phosphor in the screen; this light is the primary mechanism of film exposure. Very little of the exposure is caused by direct interaction of x-rays with the film.[1] Herz[2] has shown that the energy efficiency of a calcium tungstate ($CaWO_4$) screen varies very little with changes in x-ray energy, where energy efficiency is the ratio of light energy emitted to x-ray energy absorbed and is more commonly known as the intrinsic efficiency.

The characteristic (H and D) curve for a radiographic film relates optical density to the exposure required to produce that optical density. For constant processing conditions (barring reciprocity failure) and for film-intensifying screen systems, the shape of the H and D curve remains unchanged but the position of the curve on the exposure axis varies with the quality of the radiation producing the exposure. Normally this is expressed as a change of speed with a change in beam quality.

For certain applications, an alternative to the concept of film–screen speed is the absorbed-energy constant, defined as the energy absorbed in an x-ray screen required to produce unity net optical density on the film. Energy dependence of the H and D curve along the exposure axis is almost entirely eliminated when the optical density of the film is related to energy absorbed in the screen rather than to exposure. Variation can be eliminated only to the extent that light emitted by the phosphor is proportional to the energy absorbed by the phosphor and if direct exposure of the film by x rays can be neglected.

Unlike the conventional speed R^{-1}, the absorbed-energy constant is practically energy independent for specified development conditions and for a particular screen–film system.

Calcium tungstate screens were chosen for this investigation because the characteristics of $CaWO_4$ are well documented and the loading of phosphor (mg/cm^2) was available from the manufacturer.

II. MEASUREMENT OF ABSORBED ENERGY

An estimate of the energy absorbed in a screen can be obtained by spectroscopy, the difference between entrance and exit spectra being proportional to the absorbed energy after appropriate corrections are made for energy losses. Photons incident on the screen are removed by Compton and photoelectric interactions, primarily with the grains of the phosphor. Compton-scattered photons are removed from the beam and are assumed to undergo no further interactions with the screen. A portion of the K-fluorescence photons are absorbed by the screen. Figure 1 illustrates the experimental set up used to determine the absorbed energy and to obtain estimates of the absorbed-energy constant.

A. Equipment

The spectrometer system has been described by Fewell *et al.*[3] A 300-μ- or a 90-μ-diameter aperture, located 255.8 cm from the source, was utilized to control the photon fluence into the detector; the resultant analyzer dead time did not exceed 8%. The analyzer was operated in live-time mode; it was necessary to correct the exposures for an increase in real time depending on the count rate of the particular spectrum.

Films were processed with a Kodak model M6A-N 90-sec automatic processor; processing was monitored with sensitometric strips exposed to a Kodak model 101 light sensitometer. Optical densities were maintained to within 0.03 optical density units at 1.36 optical density. A Halsey cassette with a 3.2-mm bakelite face was utilized to support the film–screen combination during exposure.

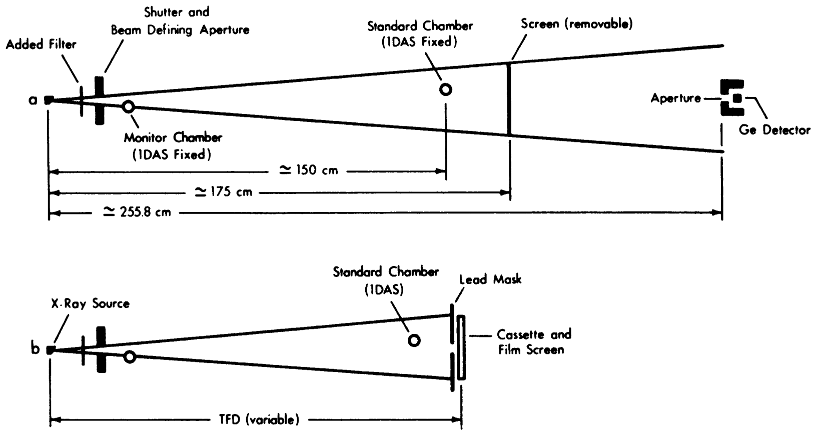

FIG. 1. Experimental arrangement used to estimate absorbed energy in an x-ray screen and ultimately the absorbed-energy constant. The x-ray source is a single-phase radiographic generator and conventional rotating-anode x-ray tube. Exposure was determined with a Victoreen model 555 electrometer and IDAS chamber; the energy correction factor was less than 3% over the range from 1.0 to 4.9 mm Al HVL. The monitor chamber was referenced to the standard chamber and inverse-square-law corrections yielded the exposure at the film–screen plane (b).

B. Procedure and results

Entrance and exit spectra for several beam qualities [see Table I(a)] were determined for a pair of U.S. Radium TF-2($CaWO_4$) screens. For a given filtration and kVp, beam quality differed slightly because tube current was varied from 0.6 to 4.4 mA. Entrance and exit spectra at one beam quality were determined for pairs of U.S. Radium STF-2, T-2, and UD-2 screens and were corrected for Ge K-fluorescent photon escape from the detector. The effect of Compton scatter was partially corrected by the relationship[4]

$$\phi_c = \phi_{unc}/\{1 - \exp[-(\mu_{en}/\rho)\rho x]\}, \quad (1)$$

where ϕ_c and ϕ_{unc} are the corrected and uncorrected differential spectra (photons $cm^{-2}\,keV^{-1}$), and μ_{en} is the energy-absorption cross section, all at energy E; ρ is the density; and x the thickness of the detector. This relationship also corrects for photons penetrating the detector and not interacting but does not fully correct for Compton distortion because the continuum is not removed from the low-energy portion of the spectrum. The difference between the entrance and exit spectra yielded the photon distribution interacting with the screen. Energy absorbed by the screen, E_{abs} (erg cm^{-2}), was estimated from the relationship

$$E_{abs} = \sum_{E_{min}}^{E_{max}} (\phi_1 - \phi_2)_E \frac{E \cdot 1.602 \times 10^{-9}}{A}, \quad (2)$$

where ϕ_1 and ϕ_2 are, respectively, the entrance and exit differential photon count at energy E (keV). A is the area of the collimator used. Correction was made for escape of tungsten K x rays from the screen.

Dividing energy absorbed, calculated from Eq. (2), by the exposure measured while accumulating the spectra yielded the absorbed-energy-to-exposure ratio (erg $cm^{-2}\,mR^{-1}$), which relates exposure and absorbed energy.

The exposure factors for the TF-2 screen and Kodak RP film were determined by inverse-square sensitometry(constant-time, variable-intensity through changes in distance) for the six beam qualities considered. The exposure factor is defined as the exposure in milliroentgens to the film–screen to produce a net optical density of 1 on the radiographic film. The exposure factor was multiplied by the absorbed-energy-to-exposure ratio to determine the estimated absorbed-energy constant [Tables I(a) and (b)]. The error associated with the exposure factor determination is approximately 8% while the error associated with the absorbed-energy-to-exposure ratio is estimated to be 5%, for a combined error in estimation of the absorbed-energy constant of 9%. The standard deviation of the estimate of the absorbed-energy constant is 11%. Within the precision of the experiment, the absorbed-energy constant of each screen was independent of x-ray beam quality.

Data obtained with a new TF-2 screen are presented in Table I(a); data accumulated for an older TF-2 screen and

TABLE I(a). Compilation of measurements on $CaWO_4$ screens. Comparison of absorbed energy (erg cm^{-2}) to produce net optical density of 1 for a pair of TF-2 screens.

Screen	kVp	mm Al added	HVL (mm Al)	Exposure factor[a] (mR)	Absorbed-energy-to-exposure ratio (erg $cm^{-2}\,mR^{-1}$)	Absorbed-energy constant (erg cm^{-2})
TF-2	100	15.0	7.42	0.655	0.538	0.35
	80	10.0	4.95	0.695	0.439	0.31
	80	1.0	2.2	1.0	0.396	0.40
	80	1.0	1.94	1.105	0.340	0.38
	60	1.0	1.62	1.20	0.276	0.33
	45	1.0	1.43	1.45	0.217	0.31
						Average = 0.35±0.04

TABLE I(b). Compilation of measurements on $CaWO_4$ screens. Comparison of absorbed energy to produce net optical density of 1 for a pair of old TF-2 screens. Back and front screens of different thicknesses.

Screen	kVp	mm Al added	HVL (mm Al)	Exposure factor[a] (mR)	Absorbed-energy-to-exposure ratio (erg cm^{-2} mR^{-1})	Absorbed-energy constant (erg cm^{-2})
TF-2	60	1.0	1.62	1.82	0.276	0.50
	60	5.0	2.85	1.34	0.383	0.51
	80	1.0	2.2	1.56	0.345	0.54
	80	5.0	3.86	1.21	0.429	0.52
	80	10.0	4.95	1.06	0.450	0.48
						Average = 0.51±0.02

[a] Exposure factor defined as the milliroentgens required to yield a net optical density of 1.

a different film-emulsion batch are presented in Table I(b). The exposure factor for this screen differs from that determined for the new TF-2 screen. Note also that the standard deviation in the absorbed-energy constant (erg cm^{-2}) for this system is small and the absorbed-energy-to-exposure ratio for the old screen agrees fairly well with that of the new screen.

Similar data are presented in Table II comparing four different $CaWO_4$ screens. Here we compare absorbed-energy constants, exposure factors, phosphor loadings (mg/cm^2), and absorbed-energy-to-exposure ratios for these screens at one beam quality (1.94 mm Al HVL). Absorbed-energy constants tabulated here include in them absorption of the primary beam by the bakelite face of the cassette.

III. ESCAPE OF *K* X RAYS

In the calculation of energy absorption, only Compton and photoelectric effects must be considered in the diagnostic x-ray region. A portion of the energy involved in the photoelectric process escapes from the screen as *K*-characteristic photons, the amount escaping depending on the thickness of the screen. Oosterkamp and Albrecht[5] calculated 30% self-absorption of *K*-fluorescence radiation for a 100-mg/cm^2 $CaWO_4$ screen. Coltman *et al.*[6] quote 27% for a $CaWO_4$ screen but the thickness of the screen was not specified.

K-fluorescence escape for $CaWO_4$ screens was calculated for a range of phosphor loadings from 30 to 300 mg/cm^2. Elemental photoelectric and Compton attenuation coefficients tabulated by McMaster *et al.*[7] were utilized to calculate the *K*-photoelectric and total attenuation coefficients for $CaWO_4$, using a weighting relationship[8]

$$(\mu/\rho)_E = \Sigma_i W_i (\mu/\rho)_{i,E}, \quad (3)$$

where W_i is the fractional weight of the ith element and $(\mu/\rho)_{i,E}$ is the absorption coefficient of the ith element at energy E. Absorption by the binder, a low-Z, low-density material, was neglected in the calculations. Using 8 (oxygen) as an approximation for Z of the plastic binder, calculations show that, above the K edge of tungsten, only 1% of the K x-ray interactions are with the binder material.

The geometry of the model used in the calculations is shown in Fig. 2. The screen was divided into slices, assuming a normally incident photon beam. The K-photon production was calculated as follows:

$$N_K = \sum_{E_{\min}}^{E_{\max}} \phi_E \exp(-\mu n \Delta x)[1 - \exp(-\mu \Delta x)]\tau_K \frac{\omega}{\mu}, \quad (4)$$

where N_K is the number of K photons produced in slice Δx, ϕ_E is the incident differential fluence (photons/cm^2 keV), $\phi_E \exp(-\mu n \Delta x)$ is the differential fluence reaching slice Δx, $n\Delta x$ is the thickness of material overlying slice Δx, $[1 - \exp(-\mu\Delta x)]$ is the fraction of photons interacting in slice Δx, τ_K is the K-photoelectric attenuation coefficient at energy E and is zero below the K edge of tungsten, μ is the total attenuation coefficient at energy E, and ω is the K-fluorescence probability for tungsten ($\omega = 0.94$).[9]

K fluorescence was assumed to be emitted isotropically from a point at the center of the slice. Therefore, the fluence was assumed to be uniform over the surface of a sphere centered on the midpoint of the slice; the ratio of the solid angle (subtended by angles $\theta 1$ and $\theta 2$) to the area of the sphere was assumed to be the fraction of K photons emitted between $\theta 1$ and $\theta 2$. The path to the surface of the screen, P,

TABLE II. Comparison of absorbed energy to produce net optical density of 1 for four $CaWO_4$ screens.

Screen	kVp	mm Al added	HVL (mm Al)	Exposure factor (mR)	Absorbed-energy-to-exposure ratio (erg cm^{-2} mR^{-1})	Absorbed-energy constant (erg cm^{-2})
UD-2	80	1.0	1.94	2.99	0.21	0.64
T-2	80	1.0	1.94	1.77	0.23	0.41
TF-2	80	1.0	1.94	1.11	0.34	0.38
STF-2	80	1.0	1.94	0.83	0.42	0.35

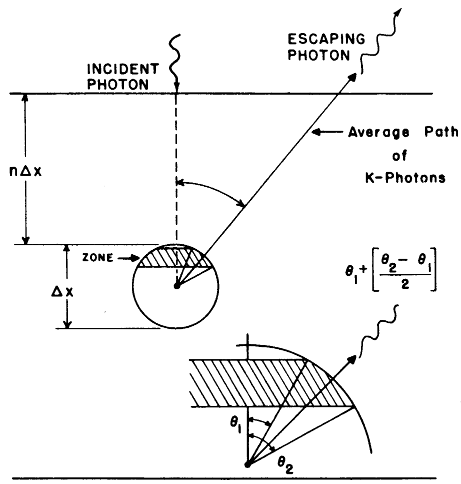

FIG. 2. Geometry used to calculate K-fluorescence escape from $CaWO_4$ x-ray screens.

was assumed to pass along the average of angles $\theta 1$ and $\theta 2$:

$$P = [n\Delta x + (\Delta x/2)]\cos[(\theta 1 + \theta 2)/2]. \quad (5)$$

The attenuation of the K x rays emitted along each path was calculated and the total energy absorbed for each slice was summed from 0° to 180°. This procedure was followed for all slices to determine the K-fluorescence-energy escape fraction as a function of phosphor thickness (mg/cm^2) (Fig. 3). The K-absorption fraction for a 100-mg/cm^2 screen was estimated to be 26%, in good agreement with the calculation of 30% by Oosterkamp and Albrecht.[5]

This treatment assumed the screen to be infinite in the plane perpendicular to the incident photons; the screen is at most several hundred microns in thickness and at least 10 cm in the plane of the screen surface. The energy of the primary photon interacting with the screen was found to have little effect on the K-photon absorption fraction. For photon energies of 70–150 keV and a thick screen (150 mg/cm^2), the variations of the calculated absorption values were 1%. The variation was less for thinner screens.

IV. CALCULATION OF ENERGY ABSORBED IN PHOSPHOR

In Sec. II, absorbed-energy-to-exposure ratios were measured. These ratios were calculated from available data on $CaWO_4$ screens. The energy absorbed by $CaWO_4$ screens was calculated for continuous photon distributions interacting with the screen phosphor. Compton scatter was considered to be lost and a portion of the K fluorescence to be absorbed by the screen. All energy involved in the L-photoelectric process was assumed to be totally absorbed in the screen. Epp and Weiss[10] published corrected spectra ranging from 45 to 105 kVp obtained with a diagnostic x-ray machine of known filtration. We used linear interpolation to obtain spectra for kVp values other than those tabulated. HVL values calculated from these spectra agreed within 0.2 mm Al with the values published.

Assuming the H and D curve to be expressible in terms of the absorbed energy and to be invariant with changes in beam quality, these spectra were used to make calculations of the exposure (mR) required to deposit 1 erg cm^{-2} in a TF-2 screen. Absorbed-energy-to-exposure ratios were then calculated for each of the entrance spectra used to obtain absorbed-energy-to-exposure ratios experimentally. These were compared to the corresponding values obtained with Epp and Weiss' spectra. Our spectra yielded 5% higher absorbed-energy-to-exposure ratios than Epp and Weiss' based on an average over eight beam qualities. The absorbed-energy-to-exposure ratios calculated from our spectra were normalized to the experimental absorbed-energy-to-exposure ratios by dividing calculated into experimental ratios, averaging over all spectra, and multiplying the calculated energy-absorbed-to-exposure ratios by the average fraction. This normalized the calculated to the experimental absorbed-energy-to-exposure ratios. These results are presented in Fig. 4 as a function of HVL.

The largest discrepancy between the experimental and calculated values was 20% at either end but good agreement was obtained in the center of the curve. Calculated and ex-

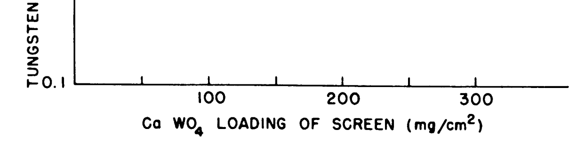

FIG. 3. Calculated K-fluorescence escape from $CaWO_4$ x-ray screens. Escape fraction (—) calculated for line spectra, 70–150 keV and 30-mg/cm^2 increments. Escape fraction (O) calculated for continuous spectra and U.S. Radium UD-2 (1), T-2 (2), TF-2 (3), and STF-2 (4) screens.

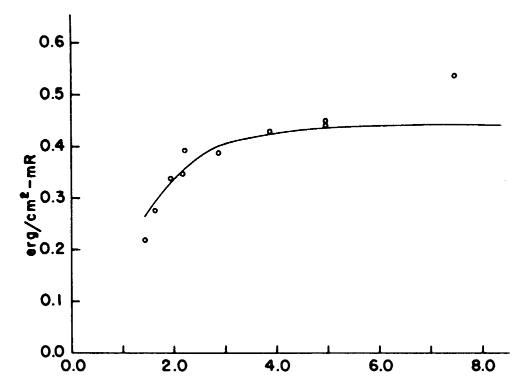

FIG. 4. Comparison of calculated and experimental values of the absorbed-energy-to-exposure ratios for a TF-2 x-ray screen, (—) calculated and (O) experimental values.

TABLE III. Comparison of experimental and calculated values of the ratio (erg cm^{-2} mR^{-1}) normalized to the value for the UD-2 screen.

Type screen	Loading[a]	Calculated	Experimental
UD-2	52	1.0	1.0
T-2	56	1.08	1.09
TF-2	103	1.63	1.62
STF-2	155	2.03	2.0

[a] Phosphor loading per screen pair (mg/cm^2).

perimental values of the absorbed-energy-to-exposure ratio are presented in Table III, normalized to the value found for the UD-2 screen in each case. Excellent agreement between calculated and experimental values was found.

V. DISCUSSION

Our studies indicate that the absorbed-energy constant for a $CaWO_4$ x-ray screen is almost independent of photon energy over the diagnostic x-ray region, a conclusion which is consistent with the data of Herz.[2]

Development of a method for specifying the speed of a screen, independent of x-ray beam quality, will simplify prediction of film-screen response to x-ray beams of varying quality. Use of a digital computer enables calculation of the energy absorbed by a screen from a continuous x-ray spectrum and predictions of net optical density for variable beam qualities and exposures, given the H and D curve of the screen-film and the absorbed-energy constant. More importantly, one can predict speed of the system for a diagnostic exposure and thus predict the optimum kVp and beam quality. The absorbed-energy constant concept is a potential approach to the specification of film-screen efficacy. One could specify the response of the screen-film system rather than specifying independently the processes: screen-emission spectrum, film spectral absorption, film speed, and incident-x-ray quality.

The photoelectric effect predominates over most of the diagnostic x-ray region; any energy absorbed by this process in the phosphor particles is locally absorbed, except that carried away by tungsten K fluorescence. The energy of photoelectrons and Auger electrons is absorbed by the phosphor particles and by the binder. Energy losses due to absorption of electron energy by the binder material were neglected. If the phosphor particles are large with respect to electron range, one can assume that most of the electron energy is absorbed in the particle. Alternatively, if the electron crosses several particles and deposits most of its energy in the particles, our calculations are valid. Loading of phosphor in the screen and particle size are important, as are the material from which the binder is made and whether or not voids exist in the binder. The maximum photoelectron energy produced by a 70-keV photon is approximately 60 keV; the range of this photoelectron in $CaWO_4$ is 7.4 μ.[11] The ratio of electron tracks in $CaWO_4$ ($\rho = 6.06$) to a low-Z material ($\rho = 1$) is 6:1. Assuming the screen to be 60% by volume $CaWO_4$, the maximum absorption of electron energy in the binder will be 10% and in practice will be less due to the presence of voids in the binder and orientation of the grains.

For the range of beam qualities from 1.43 to 7.42 mm Al HVL, calculations indicate only a 4% difference to exist in exposure transmitted through the bakelite cassette face, the difference being prominent only for low energies. Elimination of the cassette face by use of a thin rubber- or plastic-front vacuum cassette would yield different values for the exposure factors shown in Tables I and II and consequently a different value for the absorbed-energy constant. But the presence of the bakelite cassette front does not affect the conclusion of this study: The absorbed energy constant for $CaWO_4$ screens is almost independent of beam quality over the diagnostic-energy region.

We have shown that, once the absorbed-energy-to-exposure ratio for a given beam condition is known, the reproducibility of the absorbed-energy constant for $CaWO_4$ is no worse than the reproducibility of the conventional method of expressing speed as inverse exposure (R^{-1}). We see no reason why the findings of this study cannot be extended to other screens, including the rare earth screens recently introduced. The proposed method negates the necessity of determining speed as inverse exposure for a variety of beam conditions. A single quantity, the absorbed-energy constant, is proposed as a parameter similar to speed but without the dependence of speed on beam quality. The utility of expressing speed in terms of energy absorbed is the reduction of a family of characteristic curves to one curve, expressed as net optical density against energy absorbed in the screen, from which one can obtain the characteristic curve of any quality beam.

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