

U. S. GOVERNMENT

PHOTOGRAPHIC DOSIMETRY
OF X- AND GAMMA RAYS

Handbook 57



U. S. Department of Commerce
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Photographic Dosimetry of X- and Gamma Rays

Margarete Ehrlich



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Preface

This Handbook contains primary factual data and basic principles necessary for photographic dosimetry of X- and gamma rays. It was prepared in response to an urgent need felt in various places for more complete information on this topic. Since the Radiation Physics Laboratory of the National Bureau of Standards has worked extensively in this field for a number of years, it appeared that it would be helpful to other workers to publish this accumulation of material as a general information handbook.

Most of the information presented is concerned with the use of commercial photographic film for X- and gamma-ray dosimetry. Emphasis is placed on those properties of photographic emulsions that are basic to radiation dosimetry. Likewise, attention is called to limitations inherent in the methods and materials and to precautions that should be observed. Because considerable flexibility in techniques and procedures of film dosimetry is possible without appreciable effect on the end result, no attempt is made to specify all of the details uniquely.

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A. V. ASTIN, *Director.*

Photographic Dosimetry of X- and Gamma Rays

Margarete Ehrlich

1. Introduction

The need for inexpensive, rugged, but reliable, devices for the measurement of X- and gamma radiation has greatly increased the interest in the radiation response of commercially available photographic film.

The use of photographic film for X- and gamma-ray dosimetry is theoretically justifiable, but yields useful and reliable results only when based on a sound understanding of the various phases of photographic sensitometry and of its inherent limitations.

It is the purpose of this Handbook to clarify the basic concepts of the use of commercial photographic film products for X- and gamma-ray dosimetry, to organize some of the information accumulated in the Radiation Physics Laboratory of the National Bureau of Standards during the past years, and to present this information in a form that should prove useful to other workers in the field of photographic X- and gamma-ray dosimetry.

Specifically, this Handbook deals with the properties of photographic emulsions that make their use for radiation dosimetry possible. It points out the limitations of the method and discusses the precautions to be taken in the selection, exposure, processing, and densitometry of the film material. Because of the great flexibility in the techniques and procedures of film dosimetry, no attempt is made to specify them uniquely. Specific techniques should be chosen and adjusted according to local conditions.

While some of the material contained in this Handbook is general enough to apply to photographic dosimetry not only of X- and gamma rays, but also of other types of radiation, the detailed discussions are confined to X- and gamma-ray dosimetry. It is felt that due to the rather complicated nature of photographic dosimetry of such

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types of radiations as beta rays and neutron beams, it is not possible to issue authoritative statements on this subject at the present time.

2. Use of Photographic Film for the Measurement of Radiation Dose

Photographic radiation dosimetry may be defined as the measurement of the dose of a particular electromagnetic or corpuscular radiation by means of establishing a one-to-one correspondence between dose and photographic effect. It is therefore of importance to delineate the terms "dose" and "photographic effect" clearly and to understand the difficulties inherent in the measurement of these quantities.

2.1. Dose Definition

The International Commission on Radiological Units recommended that dose be expressed in terms of the quantity of energy absorbed per unit mass of irradiated material at the place of interest. The Commission decided, however, that the roentgen (defined in air) should continue to be recognized as the unit of X- and gamma-ray dose in view of its long-established usefulness, at least for quantum energies up to 3 Mev [1].¹

Measurements of the photographic effect are made in terms of diffuse transmission density [2], representing the logarithm to the base 10 of the opacity of a processed photographic film sample [3].

2.2. Measurement of X- or Gamma-Ray Dose in Terms of Photographic Density

The difficulty in relating dose to photographic density lies in the fact that, while the roentgen is a measure of radiation energy absorbed in air, the photographic action of X- or gamma radiation is essentially the result of ionization in the silver-halide crystals of the photographic emulsion and in the materials surrounding it [4, 5]. As the true absorption coefficient of air differs greatly from that of silver halides both in absolute value and in its dependence on quantum energy, and as the stopping powers of air and silver halides are not the same, it is to be expected that the ionizing action of X- and gamma radiation as a function of quantum energy for silver halides does not parallel that of air [6]. For

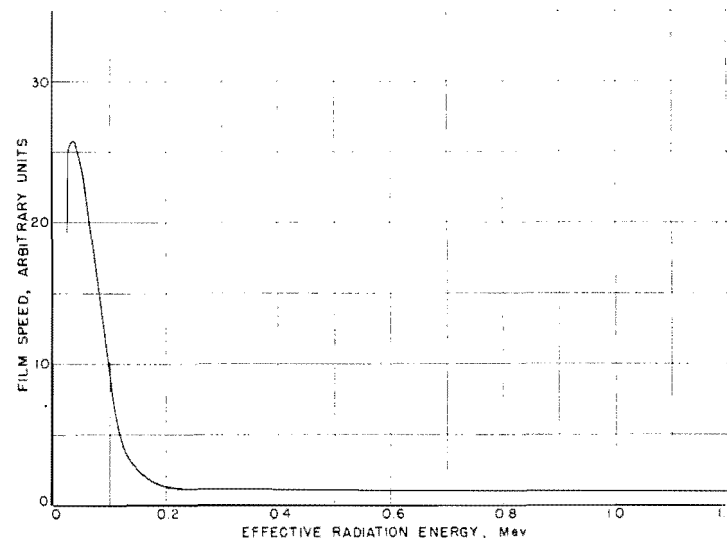


FIGURE 1. Correlation between photographic response and ionization in air as a function of energy.

radiation energies at which the range of the secondary emission produced in the emulsion proper is large compared to the emulsion thickness, the absorption coefficient and stopping power of the surrounding materials must also be taken into consideration; the situation is then even more complicated. However, a quantitative correspondence between photographic response and ionization in air can be established. Figure 1 illustrates this fact for a typical emulsion. A quantity proportional to the reciprocal of the exposure needed to produce a photographic density of 1.0 is plotted against the effective radiation energy² of heterochromatic X-radiation whose spectral width had been narrowed by means of proper filtration. The ordinate may be considered a measure of film speed [7]. The term sensitivity is used in this report as a synonym for speed. It is a quantity inversely proportional to the dose needed to produce a given photographic density. It is not to be confused with radiographic sensitivity or fault sensitivity, which for a given radiographic geometry indicates a film's resolving power and contrast [8].

² Effective radiation energy is here defined as the energy of the monochromatic X-ray beam that has the same absorption characteristics under specified conditions as the particular heterochromatic radiation.

¹ Figures in brackets indicate the literature references at the end of this Handbook.

Depending on the film type, the sensitivity below 0.1 Mev is generally 5 to 30 times that at 0.6 Mev. The sensitivity peak located at about 0.03 Mev can be explained, at least qualitatively, by the relatively strong absorption of radiation in the film emulsion compared to that in air [9, 10]. As the radiation energy increases, the absorption in the emulsion and in air tend to become proportional and the emulsion sensitivity thus remains fairly constant. For energies in the million-volt region, the sensitivity rises again slowly with energy, but this rise is very gradual and usually does not amount to more than 25 percent over the interval from 1 to 10 Mev (dose being measured in electrostatic units of charge per cubic centimeter of air with a Victoreen ionization chamber enclosed within a Lucite shell).

2.3. Limitations of Photographic Dosimetry Due to Energy Dependence

In the preceding paragraphs, it was shown how the difference between the absorption characteristics of air and of photographic emulsions (in conjunction with the materials surrounding them) causes the photographic response to radiation exposures, as measured in roentgens, to be dependent on radiation energy. Because of this dependence, dosimetric results obtained with photographic films are meaningless unless the films are calibrated with a known radiation dose, in a beam whose energy distribution is similar to that for which the dosimeters are to be used [11]. Unless the energy dependence of the instruments is sufficiently reduced, the choice of radiation energies for calibration purposes is critical up to about 0.3 Mev.

In view of these limitations, photographic radiation dosimetry may be divided into three parts, depending upon the energy of the radiation source:

(a) Dosimetry in the limited region of radiation energies between 0.03 and 0.3 Mev, in which photographic emulsions are strongly energy-dependent, but for which the radiation spectrum is fairly well reproducible in the laboratory for calibration purposes.

(b) Dosimetry in the vicinity of a number of sources, some of which are in the energy region above 0.3 Mev where emulsion sensitivity varies only slowly with energy, and some of which are below 0.3 Mev.

(c) Dosimetry of high-energy radiation in equilibrium with its secondaries, in some instances degraded to as low as 0.03 Mev, for which the radiation spectrum may or may not be reproducible in the laboratory.

Case (a) is important for radiation monitoring of areas and personnel in medical and industrial radiographic departments. In this case, film calibration charts may be readily prepared under properly chosen conditions and may be referred to for all dose interpretations. For case (b), all that is needed for the high-energy range alone is essentially one calibration chart prepared at some available high energy. However, high-energy sources are usually handled in research, medical, or industrial establishments in areas and by groups of personnel that are also exposed to radiation from low-energy sources. E. Tochilin, et al. [12], R. Baker, et al. [13], R. B. Wilsey [14], and other investigators have attempted to differentiate between the dosimeter exposures stemming from the different sources by placing a set of absorbers over portions of the film packets. In the linear portion of the density-versus-exposure curve, the ratios of the photographic densities obtained under the different absorbers are functions of energy. The authors show that if the relation between these ratios and the energy of the radiation is established, one can use it to determine the effective energy of the radiation for any given exposure. After determining the effective energy, one can then proceed to determine the radiation dose corresponding to a given density, after correcting this density by means of some tabulated multiplying factors. However, difficulties are encountered when two or more absorbers are used over the same film packet, because the radiation scattered from one absorber reaches the film portion under the adjacent absorber. An attempt has also been made to obtain a rough estimate of the radiation energy from the ratio between photographic densities caused by forward- and backscattering from given sets of metallic absorbers [15, 16]. Though somewhat cumbersome, this method seems to be useful for personnel monitoring work.

In case (c) a similar procedure to that described for case (a) may be followed when the type of radiation is readily reproducible in the laboratory. The one additional precaution is to enclose the film packets in materials suited to provide for electronic equilibrium over the emulsion surfaces. This particular phase is discussed in section 2.4. When the spectrum of the incident radiation is not reproducible in the laboratory but is known with a fair degree of accuracy either from theory or experiment, it may be necessary to calculate the response of the dosimeter to the particular radiation by weighting the spectral dose distribution according to the particular film response expected in each radiation energy interval. Only if the response is fairly constant for

the entire energy range over which the particular spectrum extends, is it possible to furnish a suitable calibration without detailed knowledge of the energy spectrum. Where such a calibration is desired, a decrease of energy dependence may be accomplished by enclosing the entire film packets in absorbers designed to reduce the amount of radiation lying in the energy range in which photographic emulsions are too highly sensitive; this tends to equalize the dosimeter response over the entire energy range.

A dosimeter working on this principle was described earlier by the author [17]. The dosimeter was not designed for personnel monitoring, but for regional survey measurements of total exposures from 1 to 10,000 r in the energy range from roughly 0.12-Mev effective radiation energy to the energy of an 11-Mv betatron. It consists essentially of a Bakelite container (density approximately 1.4), 8.25 mm thick, covered with 1.07 mm of tin, which in turn is covered with 0.3 mm of lead. The lead and tin thicknesses were calculated in such a way as to provide optimum reduction of the energy dependence of three commercial films. The Bakelite layer was made thick enough to provide electronic equilibrium in the holder wall for radiation from an 11-Mv betatron. This dosimeter is capable of measuring exposure in roentgens with an accuracy of roughly 20 percent over its useful exposure and energy range.

2.4. Considerations of Electronic Equilibrium

From the standpoint of radiation protection, a dosimeter should register a dose equal to that received by the critical organs some distance below the skin. When a beam of very high energy photons strikes a block of material, however, the secondary electrons that are projected mainly in the forward direction do not build up to equilibrium with the photon intensity until a depth approximately equal to the average electron range is reached. By equilibrium we mean the condition in which as many electrons are stopped in a slice of the material as originate there (neglecting the small exponential decrease in photon intensity). This means that as long as the material surrounding a dosimeter is thicker than the range of the secondary electrons, the secondary-electron density as measured by the dosimeter is proportional to the photon intensity at some point within the dosimeter wall.

In the case of photographic dosimeters, the condition of electronic equilibrium is comparatively well met up to about 0.3 Mev by film in its conventional wrapper. At higher

energies, difficulties arise from the fact that the range of the secondary electrons becomes greater than the thickness of the film plus paper wrapper. The secondary electrons therefore are not completely stopped in the emulsion, whereas these electrons would be absorbed in thick layers of living tissue. Thus, the photographic effect ceases to be a measure of deep-tissue dose for these energies, unless the film packet is surrounded with an additional layer of tissue-equivalent material whose thickness depends upon the energy of the photons measured. It will be seen that a film surrounded by an equilibrium layer of tissue-equivalent material will register the maximum dose that would be absorbed by a human being exposed to the same radiation intensity.

As an example of how to determine the equilibrium thickness of a given material, figure 2 shows the results of an experiment with Ansco Commercial film. In this experiment, the film was covered with varying thicknesses of Bakelite, and each film-Bakelite combination was exposed to the radiation from a cobalt-60 source for the same length of time. The photographic density of the film samples exposed in this way is plotted against the thickness of the Bakelite layer introduced over the emulsion surface. In the first portion of the curve, the film density is seen to increase markedly with increasing Bakelite thickness. This shows that the number of electrons absorbed in the emulsion increases with the Bakelite thickness.

In the second region, the curve flattens and reaches a somewhat indistinct maximum. The condition of balance between the electrons absorbed by the surrounding matter (here, Bakelite) and the electrons produced within this material, which are required for maximum dosimeter response under the given circumstances, is usually referred to as electronic equilibrium. For Bakelite used in conjunction with cobalt-60 radiation, equilibrium is seen to occur at a

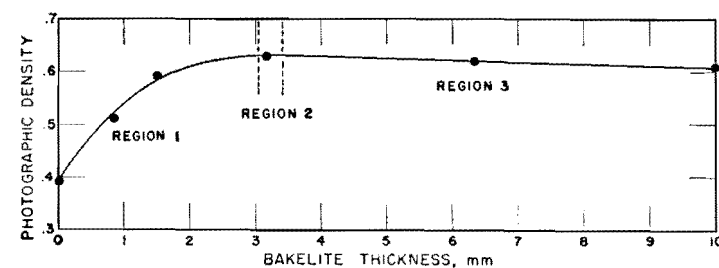


FIGURE 2. Electronic equilibrium in Bakelite, obtained with Co^{60} radiation.

thickness of about 3 mm.³ The third region of the graph is characterized by a gradual decrease of density with absorber thickness, corresponding to the attenuation of the primary radiation within the Bakelite.

Similar measurements performed with the bremsstrahlung from a betatron operated at 11 Mev gave approximate equilibrium thicknesses of 2 cm in Lucite or 2.5 cm in water.

If one wishes to make the response of a photographic dosimeter parallel that of an ionization chamber, at least for radiation energies considerably above that of the film sensitivity peak, one chooses an electronic equilibrium material whose average atomic number is close to that of air (for example, Bakelite, polystyrene, or nylon), as is customary for cavity ionization chambers that are designed to measure X- or gamma-ray absorption in terms of roentgens. If one wishes to measure a quantity proportional to the energy absorbed in living tissue, one chooses a tissue-equivalent equilibrium layer.

In some instances both metallic absorbers or emitters and low-atomic-number electronic-equilibrium layers are used around film packets. Any substance introduced between the film packet and the surrounding material produces a transition effect that disturbs the electronic equilibrium. Hence the number and type of paper layers is in general of no importance in work with X- or gamma radiation, since nonuniform paper layers do not cast differential shadows on the photosensitive surface. When, however, the equilibrium layer consists of a higher-atomic-number material, the introduction of paper seriously complicates the conditions. This is illustrated in figure 3 where the pattern of the layered

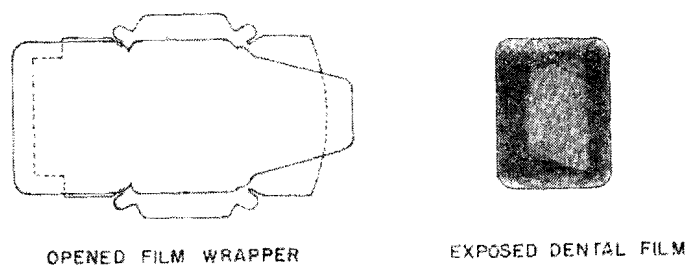


FIGURE 3. Influence of a layer of cadmium over a Co^{60} -exposed Dupont dental film packet.

³ The equilibrium thickness may be different for different exposure geometries and should be determined experimentally for each geometry.

paper wrapping is reproduced on a Dupont film, type 510. The packet containing this film was wrapped in a 1-mm sheet of cadmium during an exposure to cobalt-60 radiation.

2.5. Directional Dependence

Ideally, a photographic dosimeter should have perfectly spherical geometry for uniform response to radiation from all directions. The sheetlike configuration of photographic film thus represents a drawback inherent in the photographic method. However, since for all but the lowest energies under consideration the photographic effect is due to the secondaries produced upon absorption of the primary radiation in the material surrounding the film rather than due to absorption of the primary radiation in the film itself, the angular dependence of film exposed under electronic-equilibrium conditions to higher radiation energies is negligible. Experiments by Greening [5] indicate that films exposed under equilibrium conditions to radiation of an energy of about 0.12 Mev incident under an angle of 80 deg show about 15 percent less density than films exposed under similar conditions, but under normal radiation incidence (zero degrees). For energies both lower and higher than 0.12 Mev, Greening found the effect to be less pronounced.

When high-atomic-number absorbers are used over the film packets, this comparatively small directional dependence is increased, since the effective thickness of an absorber differs with the direction of the incident radiation. As an example, figure 4 shows the directional dependence of the Dupont film type 510 in the sketched NBS film dosimeter when exposed to a collimated beam of radiation under laboratory conditions [17]. While accurate within 20 percent for all radiation energies above 0.11 Mev, and for angles of incidence between zero and 25 deg, the NBS dosimeter underestimates the low-energy radiation components by as much as 80 percent for an angle of incidence of 80 deg. Nevertheless, it is feasible under some conditions to employ film holders in which high-atomic-number absorbers have been incorporated, even if the primary radiation source is anisotropic. For instance, the error due to directional dependence of the NBS dosimeter was shown to be negligibly small when the dosimeter was used for measurements of high-energy radiation from a point source in equilibrium with its secondaries. This is due to the essentially isotropic distribution of the low-energy components in equilibrium with the primary high-energy radiation [18]. If

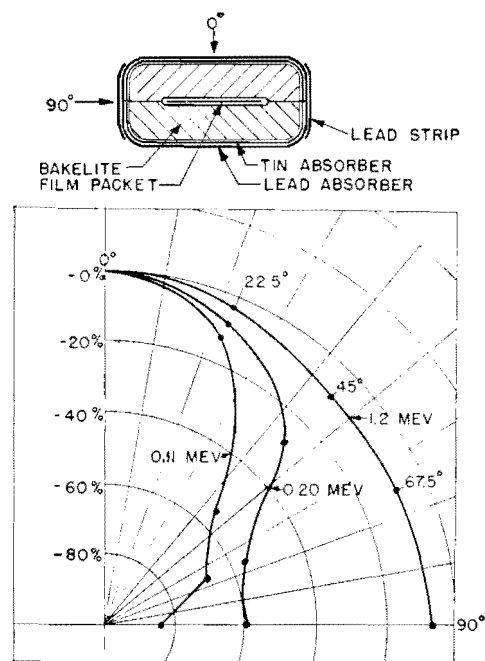


FIGURE 4. Percentage variation in dose interpretation with angle of radiation incidence, NBS film dosimeter.

absorbers are employed in photographic dosimetry of low-energy point-source radiation, a holder of higher symmetry than the NBS dosimeter may be used in order to counteract adverse directional effects. It should also be pointed out in this connection that film packets containing lead foil backing do not lend themselves to photographic dosimetry, as the foil produces a modification in the particular film's energy dependence and an increase in its directional dependence.

3. Criteria for the Selection of a Photographic Material for Dosimetry

3.1. Uniformity of Film Emulsions

The use of photographic film for radiation dosimetry requires the reproducibility of densitometric results within accuracy limits in line with the biological requirements.

Although biological accuracy limits differ considerably for the particular types of radiation effects under study and for the types and the genetic uniformity of the animals employed, there is reason to believe that at present accuracies of the order of 15 percent can be achieved for lethal and sublethal dose measurements under favorable conditions. In order to achieve comparable accuracies with photographic methods, an effort must be made to use only film material of a uniformity that permits adequate reproducibility of densitometric results. Table 1 shows a set of emulsion densities obtained on 10 different film samples of the same emulsion batch all exposed simultaneously and developed under closely controlled sensitometric conditions.

TABLE 1. Reproducibility of densitometric results

Film No.	Photographic density individual readings *					Average density for each film
85	1.59	1.63	1.57	1.58	1.61	1.60
86	1.59	1.65	1.61	1.60	1.60	1.61
87	1.58	1.64	1.62	1.60	1.60	1.61
88	1.57	1.63	1.63	1.59	1.59	1.60
89	1.57	1.62	1.62	1.57	1.58	1.59
90	1.58	1.62	1.66	1.62	1.62	1.62
91	1.60	1.60	1.66	1.63	1.61	1.64
92	1.58	1.63	1.62	1.60	1.60	1.61
93	1.58	1.61	1.61	1.58	1.59	1.59
94	1.64	1.65	1.64	1.63	1.64	1.64
Average density reading for all 10 films						1.61

* The last column represents readings at the center of the film; the other four columns represent readings in the film corners.

The maximum spread between any two individual density readings is about $3\frac{1}{2}$ percent, whereas the spread of the average readings per film is only about $1\frac{1}{2}$ percent. Such a high degree of accuracy is usually attained only when the sample emulsions are taken from the same manufacturing batch. Table 2 shows the difference between identically exposed and simultaneously processed samples of emulsions of two different batch numbers. The difference between batches is usually not too large in the case of commercial emulsions, and is in line with the data obtained by the emulsion manufacturers with exposures by visible light. The difference may be much larger in the case of experimental emulsions, as shown in the same table.

TABLE 2. *Reproducibility from batch to batch*

Commercial emulsion			Experimental emulsion		
Exposure	Density		Exposure	Density	
	Batch 1	Batch 2		Batch 1	Batch 2
149	2.05	2.30	500	0.17	0.05
244	3.13	3.00	896	.21	.12
479	3.77	3.71	2240	.73	.37
775	4.30	4.16	3580	1.41	.85
			6720	4.14	2.60

3.2. Energy Dependence

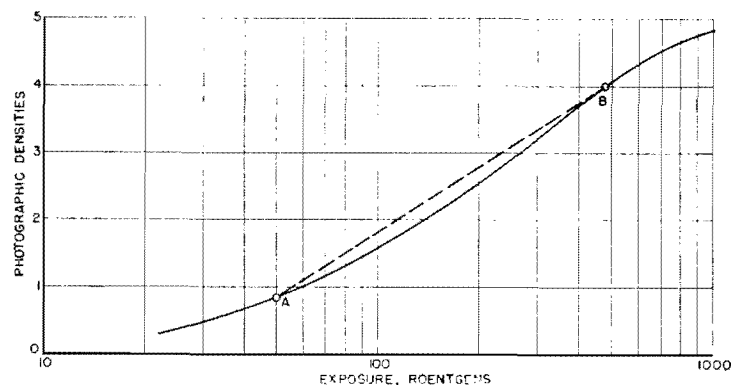
As pointed out in section 2.3, all photographic emulsions exhibit the same general type of energy dependence, the difference between the behavior of particular emulsions being quantitative rather than qualitative. Where dosimetry over a large energy range (including energies below about 0.3 Mev) is required, it is therefore necessary to use some type of metallic filter regardless of film choice, in order either to compensate for the energy dependence or to give a rough indication of the energy in question. If more than one film is needed for coverage of the dose range of interest, it is helpful to select films of approximately the same amount of energy dependence in order to make possible the use of one set of metallic filters for all of them. For some special problems of dosimetry in the medical-diagnostic and low-voltage-therapeutic range, it may be possible to eliminate the need for metallic filters without introducing too large an error by selecting films of comparatively small energy dependence in the energy range under consideration. For example, if a bare Kodak Periapical Ultra-Speed Dental X-ray film packet, Code DF-58, is exposed to X-radiation generated at 100-kv constant potential, the dose interpretation made from a calibration curve obtained at 50-kv constant potential is about 30 percent too low, which for some applications is acceptable.

3.3. Contrast, Sensitivity, and Useful Range

In order to achieve the desired accuracy in dose interpretation, it is necessary to procure films that record given dose differences in terms of large density differences. This will be the case for films for which the density-versus-exposure

curve has a sufficiently large slope. Conventionally, this curve is drawn with the abscissa on a logarithmic scale, and is then referred to as "characteristic curve." The contrast of a photographic film is related to the slope of its characteristic curve, slope at a particular film density being given by the ratio of the density increment to the increment of the logarithm of the exposure. Figure 5 shows a typical S-shaped characteristic curve, having an almost linear portion (constant slope) for intermediate densities and portions of gradually diminishing slope for very low and very high densities. For film types with characteristic curves having extended linear portions, contrast may be defined as the slope of the linear portion of the characteristic curve. Where a well-defined linear region is absent, the definition may be modified and contrast may be defined as the slope of a chord between the end points of a judiciously chosen density interval (such as, for instance, the slope of chord \overline{AB} in fig. 5).

The slope of the characteristic curve of a given film type varies with processing conditions as well as with the energy of the radiation employed for the exposure. However, it was found⁴ that over the entire investigated energy interval (from approximately 30 kev effective energy to the radiation energies from a betatron run at a peak energy of 35 Mev) the essential features of the characteristic curve of a particular film were maintained for a given type of processing and that the curves obtained with different radiation energies could be transformed into each other by a mere scaling of the

FIGURE 5. *Characteristic curve of a photographic emulsion.*⁴ NBS, unpublished data.

abscissae. Small variations in processing time and temperature did not disturb these features. This fact is the basis for the procedure of "scaling" density-versus-exposure curves as a correction for processing variations as is outlined in section 5.

Along with suitable energy dependence and high contrast, the selection of films desirable for dosimetry in a given dosage range is governed by emulsion sensitivity. The sensitivity of photographic emulsions can be defined in a number of different ways. In radiation dosimetry, it is usually found to be convenient to use as a measure of sensitivity a quantity that is inversely proportional to the radiation dose required to produce a certain photographic density. (See also section 2.) According to the density range in which the emulsion is actually used, one usually chooses a photographic density of 1.00 or 1.50. Table 3 is a compilation of values for the sensitivity of a number of photographic emulsions exposed to X-radiation of an effective energy of 0.6 Mev and developed for 5 minutes in Kodak Liquid X-ray developer at $20.0 \pm 0.1^\circ \text{C}$.

TABLE 3. Sensitivity of a number of photographic films ^a

Film type (Anso)	Sensitivity	Film type (Dupont)	Sensitivity	Film type (Eastman)	Sensitivity
	$r^{-1} \times 100$		$r^{-1} \times 100$		$r^{-1} \times 100$
High Speed	90	Type 508	135	Type K	500
Superay "A"	50	Type 502	61	Type A	50
Non-Screen	230	Type 510	13	Type 5302	1.1
Commercial	17	Type 606	1.5	Type 518-0 double-coated	0.033
Repro lith Ortho ^b	0.83	Type 1290 Ad-lux	0.44	Type 548-0 single-coated	.011

^a Sensitivity was determined at density 1 for all but the Dupont film type 502, for which it was calculated at a density 0.60.

^b Fogs with darkroom safe-light Wratten 6B, which was used successfully with all other emulsions.

While for given processing conditions contrast as well as sensitivity are inherent characteristics of a given film, they vary considerably with the choice of processing conditions (see section 5). However, for a given processing technique, contrast and sensitivity along with film uniformity determine the useful dose range of a film. Useful dose range is the exposure interval in which the error in dose interpretation by means of photographic density does not exceed a reasonable value. This value depends on individual requirements.

Table 4 shows a sample of the type of information needed to determine useful range. A series of cobalt-60 gamma exposures was given to Dupont dental-size films of type

502, which, after routine sensitometric processing, were scanned densitometrically on 25 places each. The inaccuracy in dose determination (columns 4 and 5) due to the spread in density readings on each film sample (column 3) was determined from a plot of average density-versus-exposure prepared from columns 1 and 2. The lower limit of usefulness of the film under the particular processing conditions may be selected according to the inaccuracy permissible for a particular type of application. The same procedure is then repeated for the upper limit.

TABLE 4. Inaccuracy in dose determination

Exposure	Density	Density spread over area of samples	Inaccuracy in dose determination	
			Absolute	Percentage
<i>mr</i>			<i>mr</i>	
None	0.17	0.01	20	...
30	.19	.02	30	50
50	.20	.02	30	30
100	.23	.03	40	20
300	.39	.03	36	6
500	.55	.04	50	5

4. Calibration of Photographic Dosimeters

4.1. Radiation Spectrum

It is evident from the preceding sections that a photographic dosimeter can be, at best, a secondary device for measuring radiation dose. It has also been pointed out that for X- or gamma radiation of energies below about 0.3 Mev, the dosimeters are best calibrated against the same source of radiation or a source similar to the one used in the area or around the persons to be monitored. For monitoring around high-energy-radiation sources, it is necessary not only to obtain a calibration for one or more high-energy sources, but also to check the energy dependence of the dosimeter at low energies. The choice of the high-energy source or sources depends greatly on the availability of such sources and on the suitability of a particular calibration procedure. Although a monochromatic source is preferable to a mixed-energy source when a sensitivity check at different energies above 0.3 Mev is desired, a mixed source may be

satisfactory because emulsion sensitivity changes only slowly at these energies. Under some conditions it is definitely preferable to use a mixed source, if this will better approximate the conditions under which the dosimeter will be exposed in practice.

The choice of the low-energy calibration sources is more critical because of the fast change of emulsion sensitivity with energy below 0.3 Mev (see fig. 1). Because strong monochromatic gamma sources (which would be the reasonable choice for this range) are usually not available, it is necessary to filter X-radiation in a suitable manner to narrow its spectral band-width as much as possible without too great a loss in radiation intensity [17].

4.2. Measurement of Beam Dose

The object of an intercalibration of a photographic dosimeter and a primary or secondary air-ionization standard, reading in roentgens, is to obtain a correlation between the energy absorbed and measured in the air volume of the standard and that absorbed and measured in the photographic dosimeter. For all practical purposes, measurements in terms of the roentgen obtained by means of properly calibrated thimble ionization chambers with "air-equivalent" walls of electronic-equilibrium thickness will be adequate.

It may be worth while to stress at this point that all dose measurements and calibration exposures should be carried out with a well collimated X- or gamma-ray beam. All filters and supports essential to the setup should be placed as far away from the exposure position as possible, in order to avoid scattering. Once a geometry is selected, it should be maintained throughout the experiment, both for dose measurements and for film exposures.

The inverse-square law should not be used for the determination of dose at a point different from that at which the actual measurement was performed, unless appropriate checks have indicated that the source approximates a point source with a sufficiently high degree of accuracy [19]. It is therefore recommended that the X- or gamma-radiation dose-rate for each calibration setup be measured with a suitable ionization chamber.

5. Photographic Processing

The necessity for adequate control of processing conditions for sensitometric work is generally recognized. Detailed discussions of the important phases of darkroom procedure

are to be found in the literature [20]. While the importance of a satisfactory processing technique can never be stressed too much, it is also important to realize that there is not any one set of processing conditions that produces optimum results; although some techniques may be preferable to others under certain conditions. It is usually sufficient to set up a reproducible technique. It may, but need not be, the same for all laboratories. In choosing a technique, one may be guided by the recommendations of the manufacturers of photographic materials and take into consideration the particular goal that is to be accomplished. The choice of darkroom illumination, for instance, will be guided by the sensitivity of the film to visible light.⁵ The choice of processing tanks and racks will be determined by the film size and by the volume of work to be handled. The type of processing solutions, and, to a certain extent, the developing time and temperature, may be guided by the desired useful range and contrast of the sensitive materials. Figure 6 shows the density-versus-exposure relation of the Dupont film type 510 for a series of developing times and for two different developers. The film samples were ex-

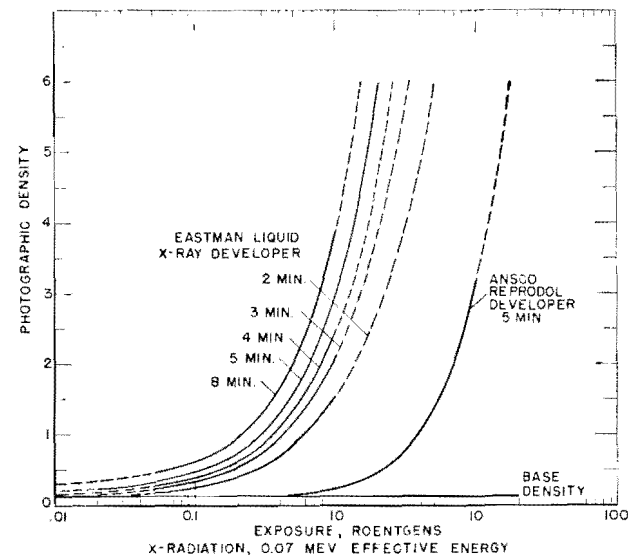


FIGURE 6. Dupont film type 510; variation of density with developer and developing time.

⁵ One must bear in mind that exposed emulsions are more sensitive to light than unexposed ones.

posed to X-radiation of an effective energy of 0.07 Mev. They were developed at $20.0 \pm 0.1^\circ \text{C}$. in Kodak Liquid X-ray developer or in Ansco Reprodol developer. The five characteristic curves obtained in the X-ray developer for different developing times form a typical family. The photographic densities obtained for a given exposure increase with increasing developing time and as long as chemical fogging does not counteract appreciably the contrast increases accordingly. The developing time is seen to be quite critical and, for this reason, an acid stop-bath introduced between the developing and fixing baths may be desirable. A comparison of the characteristic curves obtained with Liquid X-ray developer and the curve obtained with Reprodol developer shows how the useful range of a particular film emulsion can be extended by the use of developers of different characteristics. While for a developing time of 5 min in Kodak Liquid X-ray developer the useful range of the particular emulsion extends roughly from 0.04 to 2 r, the useful range in Ansco Reprodol developer is approximately 1 to 18 r. Table 5 shows similar range extensions for other films, for exposure to X-radiation of 0.6-Mev effective energy. It may be pointed out that in spite of the fact that the photographic densities obtained with Reprodol developer for any given dose are smaller by about a factor of six than those obtained with the Liquid X-ray developer, the contrast throughout the useful emulsion range is sometimes higher for Reprodol developer. However, the uniformity of density over the surface of any

one film sample suffers considerably, especially for films with thick emulsions, such as the Dupont film type 510, shown in figure 6.

Another important factor involving some choice is the type of agitation to be applied during developing. It has been shown that proper mechanical agitation either of the developing solution or of the film material or of both will enhance the uniformity of the densitometric results as well as increase the speed and contrast of the material [7, 20]. In some instances, such as in the simultaneous development of a large number of dental films, the agitation method may not present a great advantage over stationary development, provided that the processing solutions are well mixed immediately prior to development.

One particular rack, capable of holding 300 dental-size films simultaneously, was tested at the National Bureau of Standards with and without agitation. The results of this test proved that in the case of large bulky racks it is difficult to devise an agitation method that is successful in removing the used developing solution from the film surface without introducing currents that streak the emulsion. However, the same rack was used successfully without any agitation in previously well-stirred solutions to develop a large number of films simultaneously.

The effects of processing temperature, processing time, and strength of processing solutions on processing accuracies can be eliminated most effectively by processing a complete set of calibration films along with the unknown monitoring samples. These films should be of the same type and batch numbers as the monitoring films and should be exposed to radiation of known dose and energy over a dose range sufficient to cover the entire useful range of the particular films. Where such a procedure is not feasible, it may be necessary to consider in detail a number of questions for which quantitative answers can be obtained only after a considerable amount of experimentation.

In order to give an example of the type of experiments that would have to be carried out, the results of an investigation of the influence of temperature differences between the film material, the film processing racks, and the processing solutions are described in the following paragraphs.

Figure 7 is a plot of photographic sensitivity versus temperature. The experiment was carried out under two different conditions: In one, both the conventional dental-film developing rack and the films were brought to the indicated temperature; in the other, the rack was kept at room tem-

TABLE 5. *Extension of useful exposure range by the use of two developers*

Film type	Approximate useful exposure range -	
	In Kodak Liquid X-ray developer	In Ansco Reprodol developer
Ansco High-Speed X-ray.....	0.1 to 10.....	10 to 100.....
Ansco Supergy "A".....	0.5 to 20.....	10 to 800.....
Ansco Non-Screen.....	0.1 to 8.....	5 to 500.....
Ansco Commercial.....	2.5 to 20.....	20 to 300.....
Ansco Reproloth Ortho.....	25 to 1,000.....	250 to 3,000.....
Dupont type 502.....	0.3 to 10.....	10 to 100.....
Dupont type 510.....	1 to 50.....	25 to 400.....
Dupont type 606.....	20 to 700.....	200 to 2,000.....
Eastman type 5302.....	20 to 700.....	200 to 3,000.....
Kodak type 548 0 (single-coated).....	5,000 to 40,000.....	10,000 to 100,000.....

^a Fogs with darkroom safe-light Wratten 6B, which was used successfully with all other emulsions.

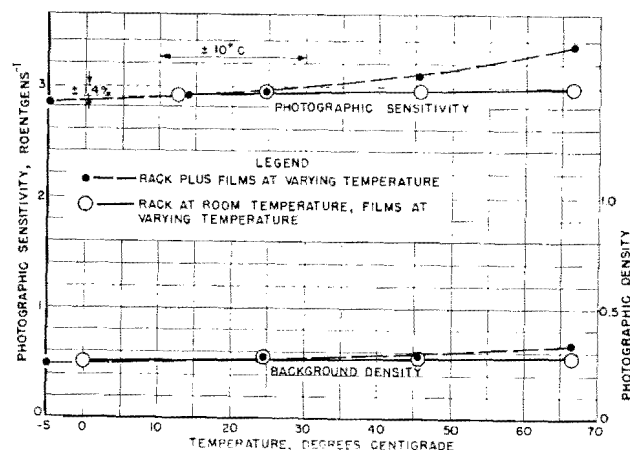


FIGURE 7. Variation of film sensitivity with film and rack temperature prior to processing.

perature and the temperature of the films alone was varied. Background controls were run for both conditions. The plots show an increase in background fog density as well as an increase in sensitivity of the exposed films for both test conditions. However, the variations are so small, even in the case of both the films and the rack at temperatures different from room temperature, that a ± 10 -deg-C difference between the processing temperature and the temperature of the film-rack combination would cause only a ± 1.4 -percent variation in sensitivity, which is well within experimental error. When the films alone are brought to a different temperature, the sensitivity variations are even smaller. One may conclude from this study that small differences in temperature between film material, conventional dental developing racks, and processing solutions do not account for large processing inconsistencies. However, it is conceivable that difficulties may arise if the developing racks employed are very large and bulky.

Two of the most common reasons for processing inconsistencies are variations in the strength and in the temperature of the processing solutions. Variations in strength may result from the use of solutions immediately after mixing (before they have reached chemical equilibrium) or from the use of exhausted or partly evaporated solutions. Crabtree and Henn [21] found that the film area that can be developed in a given amount of processing solution before any significant changes in film density become apparent differs with film

type as well as with the type of processing solution. They showed that development of about 300 sq in. of heavily exposed Kodak Blue Brand X-ray film in 6 gal of Kodak Liquid X-ray developer produces a decrease of 0.1 in density in the linear portion of the characteristic curve, while there is no appreciable density decrease with Kodak No-Screen X-ray film under the same conditions. Results of tests illustrating the importance of maintaining a constant processing temperature are shown in figures 8 and 9. The curves shown in figure 8 were obtained with X-radiation of 0.07-Mev effective energy. Kodak Liquid X-ray developer was used for processing at a number of different temperatures. The temperatures were maintained with an accuracy of ± 0.1 deg C. The slope of the curves is seen to decrease with decreasing temperature. The emulsion sensitivity decreases as well. The extent of the decrease is seen to vary with emulsion type. This is brought out in figure 9, where the relative sensitivities (proportional to film density divided by the exposure in roentgens) are plotted against developing temperature. While with Dupont film type 510, a $\pm \frac{1}{2}$ -deg change in temperature produces a change in sensitivity of almost ± 5 percent; the same change in temperature produces only a ± 2 -percent change in sensitivity with Dupont film type 1290.

Where it is not possible to eliminate the influence of processing conditions entirely by developing a complete set of

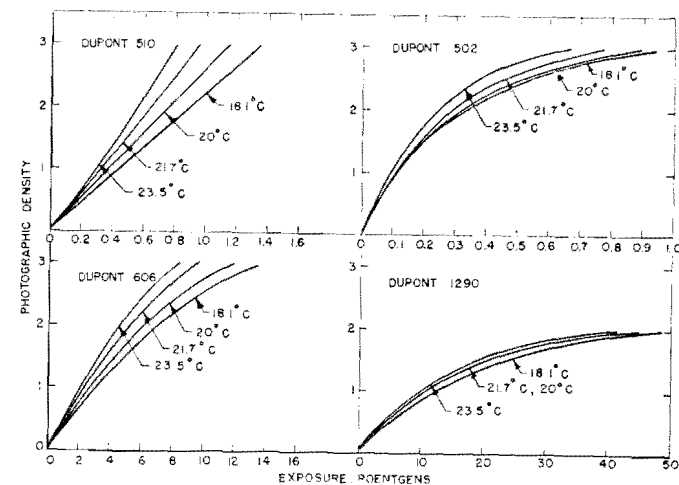


FIGURE 8. Influence of developing temperature on film characteristics.

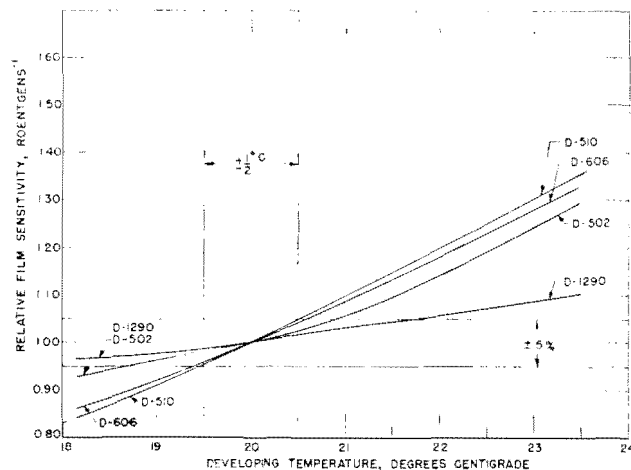


FIGURE 9. Variation of film sensitivity with developing temperature.

calibration films along with the monitoring samples, processing conditions can be checked by developing a small number of films exposed to one or two known dosages of a given radiation together with the samples.¹ In this way, the magnitude of the uncertainties in processing can be estimated. The ratio between the control density actually obtained and the density corresponding to the particular exposure on the calibration curve has been used by some authors as the density-correction factor for the monitoring samples. They multiplied the actually obtained densities by the correction factor and used the corrected densities for the dose interpretation from the density-versus-exposure curve [12]. This procedure is adequate as long as the unknown densities lie within the range in which photographic density is a linear function of exposure. If this is not the case, it is advisable to modify the described correcting procedure by applying a correction to the exposure scale of the originally available curve rather than to the densities of the monitoring samples. The proper correction factor to be applied to the exposure scale is the exposure corresponding to the control-film density corrected for background fog, as interpreted on the available curve, divided by the exposure that the control film actually received.

¹ It was shown in the example of processing temperature variations that in some instances the extent to which processing variations affect film density depends on the emulsion type. For reliable results, it is then necessary to use control samples of the same emulsion types and batches as are used as monitoring samples.

6. Photographic Densitometry and Interpretation of Densities in Terms of Exposure

With the advent of highly stabilized photoelectric densitometers, densitometric procedures have become a matter of routine and, with sufficient care, are reproducible within 0.02 in density. Two different densitometric procedures are now in use in the various laboratories. In some laboratories, gross densitometric readings are taken, the zero setting of the instrument being the setting for the case of "100-percent transmission." In other laboratories the zero point of the instrument is adjusted to signify the transmission of an unexposed film sample, developed in the same manner as the monitoring samples and coming from the same film batch (net density reading). These two methods are equivalent only if calibration films are developed together with the monitoring samples or if the "background" density of later developed samples has not changed appreciably because of fogging of the emulsion between the time the calibration curve is prepared and the time the density of subsequently exposed and processed monitoring film samples is interpreted in terms of dose.

In the case of a change in background fog, the two methods of densitometry require corrections of a different kind and magnitude, if serious mistakes in dose interpretations are to be avoided. When gross densities are read, an approximate correction can be carried out in the following way:

An unexposed film sample that otherwise has the same history as the monitoring films is developed along with these monitoring films. The film densities are then interpreted in terms of exposure from the original calibration curve. The true exposure received by the monitoring films is obtained by subtracting from the exposure value obtained from these films, the exposure corresponding to the density above base and fog.

In the case of net density readings, no further correction is necessary, provided that the monitoring films are not massively fogged.

7. Storage of Photographic Material

Little quantitative information is available on the destructive influence of humidity and temperature on photographic emulsions, be it by fogging of unexposed or exposed material or by fading of the latent image. Film companies usually recommend a temperature of about 10° C and a

relative humidity of about 30 percent as optimum for film storage. The humidity of the atmosphere in contact with the emulsion can be readily kept constant by enclosing the individual packets in moisture-proof bags. The effect of storage temperature differs in magnitude with emulsion type. It is generally true that very sensitive emulsions fog more readily than less sensitive ones, but there is reason to believe that the latent image is less liable to fade in the sensitive emulsions. The effect on photographic film of high temperatures prior to exposure is usually not considered excessive for short-time storage at temperatures up to 60° or 65° C. It is, however, suggested that for any particular choice of storage conditions the effects of temperature and humidity on the film material before and after irradiation should be tested by developing sample films at regular intervals and inspecting their condition.

Table 6 gives some data on the effect of high storage temperatures but low storage humidities on two film types both before and after exposure. Exposures were administered while the films were at room temperature (about 24° C). Figures 10 and 11 show the effects of an 8-day storage after exposure of the two film types of table 6 at normal room temperature (23° to 27° C) and relative humidities not exceeding 60 percent. While the fading of the latent image of the Dupont film type 510 (a radiation monitoring film) causes a decrease in dose interpretation of only 15 percent

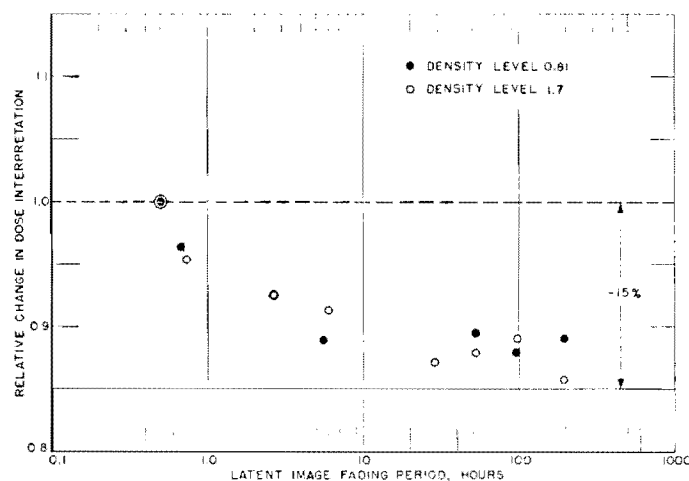


FIGURE 10. Dupont film type 510; fading of latent image.

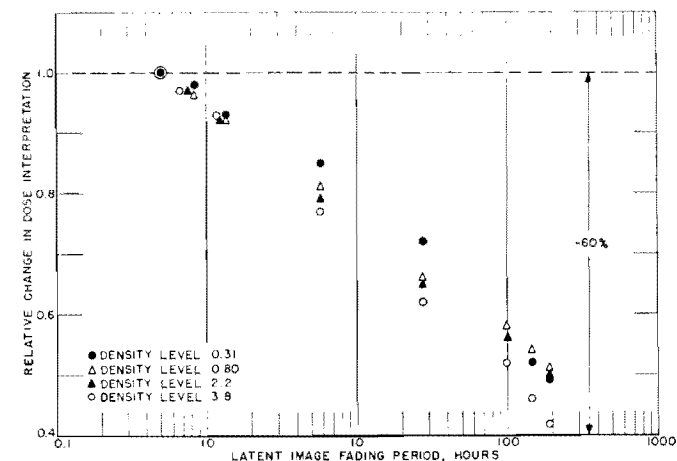


FIGURE 11. Kodak Spectroscopic film type 548-0 (double-coated); fading of latent image.

over this period of time, the fading of the Kodak film type 548-0 double-coated (a spectroscopic film), causes a decrease in dose interpretation of 60 percent over the same length of time.

TABLE 6. Effect of dry warm air on two different film types

Film type	Film condition	Change after heating to —		
		≈ 50° C	≈ 65° C	≈ 75° C
Dupont type 510.	Unexposed (background density 0.13).	No change after 48 hr.	Fogging to density 0.60 after 17 hr.	Fogging to density >1 in less than 6 hr.
	Pre-exposed.	No change after 48 hr.		Fogging to density >3 in less than 6 hr.
Kodak Spectroscopic film type 548-0 (double-coated).	Unexposed (background density 0.031).			Fogging to density 0.25 after 6 hr.
	Pre-exposed.		50-percent fading after 8 hr.	

The considerations above apply to storage only. It was assumed throughout this discussion that all exposures were made in a laboratory at temperatures between 23° and 27° C. However, the work of Morgan [22] on four different

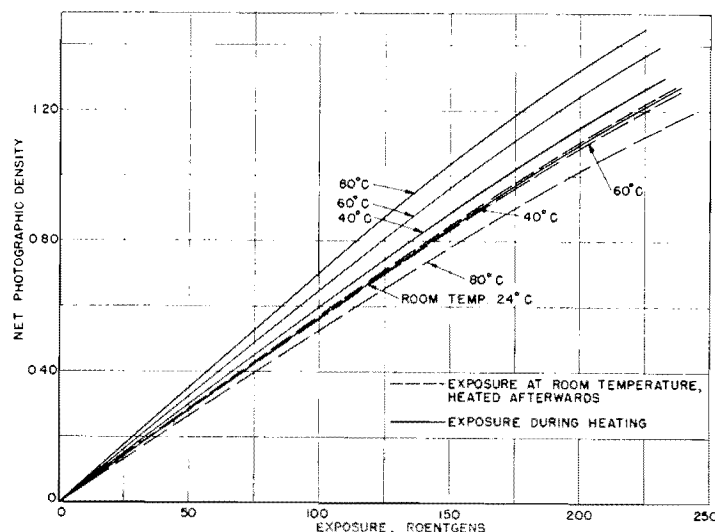


FIGURE 12. Dupont film type 606; change of film characteristics with storage temperature during and after exposure.

radiographic film types indicates no variation of sensitivity to X-radiation over a temperature range from -10° to $+60^{\circ}$ C. on two of the tested films, a variation of about 15 percent on a third one, and a variation of 40 percent on a fourth. These results were essentially confirmed in this laboratory for different film types. The tests performed at the Bureau indicate, furthermore, that heating during latent-image formation produces different results from heating after the latent image is formed. This is shown in figure 12 for Dupont film type 606. In view of the marked changes in the density-versus-exposure curves with changing temperatures, it seems advisable to protect the films from large temperature changes at all times or, where this is impossible, to determine the effects of high temperatures during storage and very high or very low temperatures during calibration, in order to be able to apply certain rough corrections.

8. Summary

In order to facilitate the use of this Handbook for practical photographic dosimetry and to highlight once more the dangers and pitfalls of the photographic method for meas-

uring radiation dose, a brief summary is now given of its most important ideas.

The photographic action of X- and gamma rays can be brought into one-to-one correspondence with radiation dose as measured in roentgens, and it is therefore possible to use photographic emulsions for X- and gamma-ray dosimetry. However, before attempting to adopt a certain dosimetric procedure, one should familiarize oneself with the following facts:

1. The response of photographic film depends on the energy of the X- or gamma radiation, used for the exposure especially in the energy region up to about 0.3 Mev. The film should therefore be calibrated with a radiation spectrum similar to that encountered in actual use, unless the energy dependence has been sufficiently counteracted by the effect of a selectively absorbing film holder.

2. The response of photographic film to penetrating radiation (electromagnetic or corpuscular) depends on the material surrounding the emulsion as well as on the inherent characteristics of the emulsion itself. In the case of X- or gamma radiation it is necessary to surround the film with material sufficient for electronic equilibrium in order to obtain reproducible results under varying conditions.

3. Sensitivity and contrast of a photographic emulsion are materially influenced by the type of developing agents, their age and temperature, as well as by the developing time, the type of film developing rack, and the mode of agitation during the developing process. Processing conditions should therefore be kept as nearly constant as possible. If at all feasible, calibration films should be processed along with the monitoring films. Where this is impossible, control films should be used to adjust the calibration curves in such a way as to compensate for any changes in processing conditions.

4. The recommendations of the manufacturers may be followed regarding best storage and processing procedures of the film material, its useful life span, and the fading characteristics of the latent image under normal conditions. Where unusual circumstances are expected to arise or no information can be obtained from the manufacturers, further tests should be performed on the particular film types.

When used in conjunction with the attached reference list, this Handbook should enable the reader to become sufficiently familiar with the fundamental processes of photographic X- and gamma-ray dosimetry to set up his own dosimetric laboratory.

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