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The Use of Film Badges for Personnel Monitoring

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THE USE OF FILM BADGES FOR PERSONNEL MONITORING

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FOREWORD

Previous Manuals in the Agency's "Safety Series" (particularly Nos. 1, 2, 3 and 4) have made or quoted various recommendations regarding the use of photographic film in personnel monitoring. The present Manual offers a much more exhaustive review of the subject for use as a guide to the implementation of those recommendations. Dr. Margarete Ehrlich, of the United States National Bureau of Standards, wrote the Manual as a consultant to the Agency. The author alone is responsible for the views expressed in this Manual.

Like the earlier publications in the "Safety Series", this Manual will appeal primarily to persons working with radionuclides, whether natural or artificial. However, the principles of photographic personnel monitoring apply to any kind of ionizing radiation, regardless of its source, and are applicable by users of X-ray machines, neutron generators or particle accelerators.

The Manual contains a large number of references to the literature, including relevant national and international recommendations. Since such a large amount of literature is already available, the material has been handled selectively with a view to including mainly information not previously collected in a form suitable for the present purpose.

May 1962

SIGVARD EKLUND
Director General

CONTENTS

CHAPTER 1

INTRODUCTION

Photographic film is fairly inexpensive and durable and, as a result of irradiation, its radio-sensitive components, the silver halide crystals, undergo relatively permanent changes. With proper calibration, the optical density of the developed and fixed photographic film can be related to radiation exposure. The optical density is not altered by repeated evaluation procedures and does not change grossly with storage over a prolonged period. For this reason, photographic film is, in some countries, accepted as *medico-legal evidence* of radiation exposure.

For personnel monitoring, photographic film is, as a rule, carried in dental-size packets, contained in suitable holders. Such holders, containing packets of photographic film, are now often referred to as "film badges", regardless of whether they carry personnel identification such as photographs, passes, etc.; i. e., regardless of whether they are complete identification "badges".

Personnel monitoring with photographic film is today the method of choice in many laboratories [1], although it requires a certain amount of apparatus for film calibration, processing and densitometry, as well as a conscientious technical staff. Photographic personnel monitoring is particularly recommended where it is important to increase the awareness of radiation hazards among radiation workers, health-physics experts, and administrators, and, at the same time, alleviate unwarranted fears, but where no need exists for distributing routinely a large number of delicate radiation instruments requiring a considerable amount of maintenance (such as, for instance, pocket ionization chambers and pocket dosimeters of the ionization type).

Where frequent changes in the working routine make it desirable to provide for an immediate determination of exposure dose, either by the individual himself or by the health-physics expert in charge, it is often recommended that film badges be supplemented by pocket dosimeters of the ion-chamber type. (For an explanation of the difference between pocket ionization chambers and pocket dosimeters of the ionization-chamber type, see, for instance, the IAEA publication "Safe Handling of Radioisotopes" [2].)

Pocket chambers and pocket dosimeters indicate exposure dose without any previous processing, as is necessary for photographic film. They do not have to be calibrated each time they are used, but require only occasional calibration checks. They should be submitted to regular expert tests for malfunctioning, spontaneous leakage, etc. Recharging the instruments for use destroys the primary record of radiation exposure. In fact, in most pocket ionization chambers, which, for reading, have to be coupled to an electrometer circuit, the mere process of reading alters the exposure indication. Recharging requires considerable care.

Experience has taught that a film-badge service works more efficiently for a larger group of people, say, for a hundred or more persons, than for five or ten. Therefore, it is often recommended that a centralized service be run for a number of individual laboratories. The monitoring centre should be located close enough to the individual laboratories for an occasional personal contact in case of doubt regarding an exposure assessment, or in case the necessity arises to advise a worker, or the health-physics expert, of a potential radiation hazard.

In the following chapter, a review is given of the more common photographic terms and concepts of importance in photographic dosimetry. In the third chapter, the application of the photographic technique to personnel monitoring is discussed. The last two chapters deal with problems of a more practical nature, of importance to the person who is actually establishing a film-badge service: in chapter 4, space, equipment and manpower requirements are presented, and in chapter 5 specific examples are given of photographic personnel-monitoring procedures, as they are now carried out in existing monitoring laboratories.

CHAPTER 2

THE PHOTOGRAPHIC PROCESS, A REVIEW OF TERMS AND CONCEPTS*

2.1 Photographic film:

An acetate or plastic base, covered on either one or both sides with a light-sensitive gelatinous layer (the emulsion), containing small silver halide crystals (grains). The films usually used for personnel monitoring have a high content of silver bromide; their grains are fairly spherical and, as a consequence, the energy loss of ionizing radiation within the emulsion is relatively isotropic.

Average diameter of undeveloped grains: 0.1 μm or less, to 1 μm, according to film-type used (lower limit corresponding to nuclear emulsions).

Emulsion thickness: according to type, 2 to 5×10^{-3} cm.

2.2 Latent image:

A microscopic aggregate of silver atoms, usually formed through the interaction of light, or high-energy ionizing radiation and its secondaries, with the grains. During the process of development, the latent image acts as a centre for further reduction of the silver halide crystals. An emulsion fog or a spurious latent image (latent image not due to irradiation) may be formed during the process of emulsion manufacture and coating, or during emulsion storage. In the finished emulsion its formation usually is favoured under the influence of physical pressure and by an interplay of high ambient temperatures, high relative humidities, or high concentrations of chemicals in the atmosphere.

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* The pamphlets "Photographic Dosimetry of X- and Gamma Rays" [3] and "Report of the International Commission on Radiological Units and Measurements [ICRU]" [4] contain further discussions of the photographic process. For details, see also, for instance, the books "The Theory of the Photographic Process" [5], „Grundriß der Photographie und ihrer Anwendungen besonders in der Atomphysik" [6], "Radiation Hygiene Handbook" [7] and "American Standard Method for Evaluating Films for Monitoring X- and Gamma Rays having Energies up to 2 Million Electron Volts" [8].

2.3 **Latent-image fading:**

Regression of the latent image, i. e., disintegration of aggregates of developable free silver. Fading characteristics of the photographic latent image depend on the type of emulsion, the temperature, humidity and chemical contamination of the atmosphere, as well as on the type of radiation exposure [9]. The increase of latent-image fading under the influence of high relative humidity during exposure and storage is particularly pronounced, the effect of high relative humidity being interrelated with temperature effects in a complicated manner [10, 11, 12]. At a given relative humidity and temperature and for a given type of radiation, fading usually is highest in fine-grain emulsions, such as are used for nuclear-track work.

2.4 **Photographic processing:**

A term usually embracing a number of separate concepts:

Developing — the process of chemically reducing to atomic silver all the silver ions in irradiated grains bearing latent image, with the result of a visible darkening of the emulsion;

Fixing — the process of removing the unreduced silver halide grains and hardening the emulsion, thereby rendering the developed image permanent;

Washing — thorough removal of processing solutions from the film emulsion before and after fixing;

Drying — desiccation of the film emulsion to equilibrium with the ambient atmosphere, best accomplished in dust-free air at room temperature or at least without excessive heat.

The use of an acid stop-bath that instantly interrupts the developing action is preferable to washing in pure water after development. After the final washing following fixation, the films may be dipped into a wetting agent that insures uniform drying without the formation of "water marks".

For the best results, it is desirable to adhere as closely as possible to the processing rules laid down by the manufacturer of the films and processing reagents.

2.5 **Reciprocity failure:**

Failure of the photographic (radiographic) effect to be constant for a given product of radiation intensity and exposure time, independent of exposure rate and time separately. For a given film-type and a given type of radiation, it occurs whenever the absorption of more than one photon (i. e., more than one interaction) is required for the production of a developable silver aggregate (latent image).

At very low intensities of light, reciprocity failure occurs when the rate at which silver ions are reduced through the interaction of light photons with silver halide molecules is slower than that of the recombination of free silver and halogen. At very high intensities, reciprocity failure is due to regional saturation effects, occurring when interactions take place in such rapid succession that the free halogen atoms are not removed fast enough, and a high probability exists for their recombination with the free silver.

For high-energy ionizing radiations, one interaction often suffices for the formation of a developable latent image, provided development is vigorous; in this case, the radiographic effect is independent of radiation intensity. With visible light, there is always more than one interaction required.

2.6 Optical transmission density:

The logarithm to the base ten of the film opacity, i. e., the ratio of the light intensity measured without and with the film in the light path. One usually discriminates between specular and diffuse density [5]. What is measured with the photometers ("densitometers") used in personnel monitoring as a rule comes close to diffuse density. Where the term optical density is applied to photographic papers rather than to film, it signifies reflection density, which is defined in an analogous way.

The optical density of the unexposed film stems from the density of the base and the "fog" of the emulsion layer as such, i. e. from free-silver aggregates not due to radiation exposure, arising from spurious latent images (see under "latent image"), or produced during development. Development fog varies with the type of developer; it increases with developing time.

The difference between the optical density of an exposed film (or paper) and that of an unexposed film (or paper) of the same type and batch, processed simultaneously with the exposed film, is referred to as net optical density.

2.7 Characteristic (or Hurter and Driffield) curve:

A plot of the optical density (usually net) as a function of the logarithm to the base ten of the exposure (see Fig. 9, p. 52). Except for small variations which may occur from emulsion batch to emulsion batch, this plot has a characteristic shape for each type of film at constant conditions of exposure and processing. In some instances, a plot of density *vs.* exposure on a linear scale or on a log-log scale may be more useful, particularly in the absence of reciprocity failure; in this case, the plot results in a straight line for low densities. In the absence of reciprocity failure the shape of the characteristic curve of a film is essentially the same for exposures to different types of radiation; the curves may be shifted, however, parallel to each other, along the exposure axis.

2.8 **Photographic sensitivity:**

A quantity inversely proportional to the exposure required for a given net optical density. One may define it simply as equal to the ratio of a particular net density to the exposure required to produce this density. According to the units in which exposure is measured, one often distinguishes between dose sensitivity and flux sensitivity. In this Manual, the term "sensitivity" will signify dose sensitivity. For a given type and batch of photographic film and for given conditions of processing, photographic sensitivity varies with the type and energy of the incident radiation.

2.8.1 *Energy-dependence of photographic sensitivity for charged particles*

In the energy region of interest in personnel monitoring, charged particles transfer their energy to the silver halide grains mainly through collisions with atomic electrons along their paths. As a consequence, the photographic sensitivity for charged particles increases with the path-length of the particle in the emulsion, and, up to the point where one single interaction between the incident particle and the silver halide grain is sufficient to make this grain developable, also with the energy loss per interaction. Any further increase in the energy loss within a particular grain causes an increasing amount of particle energy to be wasted on the already developable grains, which results in a decrease of the photographic sensitivity.

Because of its dependence on the path-length of the particle in the emulsion, photographic sensitivity also varies with the direction of particle incidence and with the type of particle. For instance, for protons whose ranges for a given particle energy are smaller than those of electrons by three orders of magnitude, the sensitivity is much smaller than that for electrons.

In general, the sensitivity of photographic emulsions to monoenergetic electrons of perpendicular incidence increases sharply with electron energy until the depth of penetration of the electron within the emulsion is comparable to the emulsion thickness. This is the case at around 0.1 MeV for single-layer emulsions and at around 0.3 MeV for double-layer emulsions [14]. As the energy of the electrons is further increased and, correspondingly, the electrons lose less and less energy in the emulsion proper, the sensitivity gradually decreases. In practice, the resulting energy-dependence of the electron (or beta-ray) sensitivity is smaller than would be expected, mainly because of the essentially diffuse incidence of the particles on the emulsion, and the resulting diminished dependence of electron path-length in the emulsion on electron energy [14, 15, 16]. Furthermore, in the electron energy range for which the average energy loss per interaction is close to its minimum and thus does not vary strongly with energy, sensitivity is expected to change only slowly with electron energy, regardless of whether the energy loss per grain is sufficient for grain developability. (For electrons in photographic emulsions, the minimum energy loss per unit path-length occurs in the neighbourhood of 1 MeV, while it lies in the GeV range for heavy particles.)

Also, in the case of beta-ray sources, the filtration in the path of the beta-rays has no great influence on photographic sensitivity, since the energy spectrum of the beta-rays from a given beta-ray source varies only very slowly with absorber thickness [14, 16].

2.8.2 *Energy-dependence of photographic sensitivity for photons and uncharged particles*

Photons, neutrons, and other uncharged particles lose their energy to the emulsion largely through the ionization produced by their charged secondaries, released either in the emulsion proper or in its immediate vicinity. Because of the complicated variation of the photon absorption-coefficient with photon energy, showing the well-known photoelectric absorption edges (at 25.5 keV for silver and at 13.5 keV for bromine) and, as a consequence, large absorption maxima, the energy-dependence of the photon sensitivity of photographic film is quite high, particularly in the energy region in which photoelectric absorption prevails, i. e., below 100 keV. (In fact, the sensitivity of most photographic emulsions is 20 to 40 times higher to photons of an energy in the vicinity of 40 keV than to photons of an energy around 1 MeV. See Fig. 20, p. 67.)

The neutron sensitivity of a photographic emulsion can be deduced roughly from the sensitivity of the charged particles produced by the interaction of the neutrons with the photographic emulsion [17].

For high-energy photons or neutrons, for which the range of the charged secondary particles produced by the incident radiation is larger than the emulsion thickness, a sensitivity loss is recorded, unless the film is exposed under conditions of charged-particle equilibrium, i. e., covered with a sufficiently thick layer of emulsion-equivalent material to insure that — on the average — for every charged particle leaving an infinitesimal volume surrounding any one point within the emulsion, a particle of practically the same energy enters the volume.

CHAPTER 3

APPLICATION OF THE PHOTOGRAPHIC TECHNIQUE TO PERSONNEL MONITORING*

3.1 QUANTITY TO BE MEASURED

It ist usually difficult to measure a quantity that is representative of the effect of ionizing radiation on living human tissue. Therefore, in the case of X- or gamma-rays up to around 3 MeV, measurements are usually carried out in terms of exposure dose in roentgen. In the case of corpuscular radiations, it is often practical to measure incident-particle or energy flux. From these measured quantities it is at least theoretically possible to calculate the absorbed dose with the aid of the proper conversion factors, and to determine the "RBE dose" of ionizing radiation in living human tissue. (The RBE dose (in rem) is equal to the absorbed dose (in rad) in the particular tissue under consideration, weighted by the relative biological effectiveness of the particular radiation in that tissue [4].)

The importance of a particular tissue is to a large extent determined by biological considerations, but it also depends on the spatial dose distribution produced by the type or types of incident radiation [22]. This distribution is both a function of exposure geometry and of the penetrating power and the biological effectiveness of the particular radiation; it is an important factor in the choice of a suitable position for the dosimeter on the human body. In personnel monitoring it may be a good practice to have the individual carry dosimeters on the parts of the body on which the dosimeter readings are habitually high [23]. However, if the high readings occur on the extremities of a person working around penetrating radiation, it is advisable to have the person carry one badge on the trunk and a supplementary badge on the extremities.

3.2 CALIBRATION OF PHOTOGRAPHIC FILM OR FILM BADGE

If the photographic film (or film badge) is to be used as a personnel dosimeter, a quantitative relation has to be established between the

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* For details on dosimetry concepts in general see "Radiation Dosimetry" edited by Hine and Brownell [18], ICRU Report (1959) [4], NCRP Report (1957) [19], NCRP Report (1960) [20] and „Dosimetrie und Strahlenschutz" by Jaeger [21].

photographic effect and the radiation exposure. For this purpose, the film (or film badge) has to be calibrated.

Although photographic film is one of the oldest indicators of ionizing radiation, it is not ideally suited for quantitative measurements of personnel exposure. There is a considerable difference in the chemical composition of film and living tissue, causing the film response to radiation to be different from that of tissue, both in absolute magnitude and in its dependence on radiation energy. Also, the relation between exposure to a given type of radiation and photographic density is not always linear (although, in the absence of reciprocity failure, such linearity exists, at least for low values of photographic density).

Only for radiation energies for which the film thickness is small compared to the mean-free-path of the (primary or secondary) corpuscular radiation mainly responsible for the photographic effect is it possible to simulate tissue conditions, and thus approximate tissue response. In the case of high-energy photons or neutrons this may be accomplished by surrounding the films with tissue-equivalent material in which corpuscular equilibrium is established (for definition see section 2.8.2). In personnel dosimetry, this method is not generally applicable, since one single film (or at least one single film badge) is usually used to monitor a number of different types of radiation, some of which (for instance electrons up to 1 MeV) would be completely absorbed in a tissue-equivalent layer of thickness sufficient to establish electronic equilibrium for 1-MeV X- or gamma-radiation. In fact, even the opaque paper layers of the film packets absorb certain types of corpuscular ionizing radiation contributing to the dose to superficial human tissue not covered by clothing, and thus prevent these types of radiation from being measured.

In the case of fast-neutron monitoring with nuclear-track emulsions, one often establishes proton equilibrium in a tissue-equivalent material surrounding the emulsion. In this way, one decreases the energy-dependence of the neutron response and also enhances the absolute magnitude of this response. Nevertheless, the fast-neutron response is so low that — in the exposure range of interest in personnel monitoring — dose interpretation necessitates counting of individual particle tracks rather than measuring an over-all density.*

Because of the difference in film response to different types and energies of radiation, the calibration of photographic film for use in dosimetry would, in theory, necessitate the determination of characteristic curves for all types of radiation to be monitored, and for a sufficiently large number of different energies of each of the radiation

* One great advantage of this rather cumbersome procedure is its selectivity, a feature that is of particular importance because fast-neutron fields are, as a rule, associated with gamma- and beta-ray fields. Through track-counting, one is in a position to separate the effect of neutrons from that of gamma- and beta-radiation.