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SAFETY SERIES No. 8

The Use of Film Badges for Personnel Monitoring

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1962

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THE USE OF FILM BADGES FOR PERSONNEL MONITORING

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SAFETY SERIES No. 8

THE USE OF FILM BADGES FOR PERSONNEL MONITORING

by Dr. MARGARETE EHRLICH

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA 1962

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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.

SIGVARD EKLUND
Director General

May 1962

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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].)

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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.

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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].

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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

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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

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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

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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.

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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].

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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.

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types. Such a procedure would yield the photographic sensitivity as a function of radiation energy for each type of radiation.

In practice, not all the phases of this procedure need be carried out routinely. First of all, when the reciprocity law holds, the characteristic curves obtained with different types of radiation and different radiation energies have practically the same shape. Thus, it is not necessary to repeat the density-*vs.*-exposure curves in detail for all types and energies of the radiations, but it suffices to obtain enough points to locate the characteristic curves with respect to the log-exposure axis. Also, in some instances, one is in a position to carry out the calibration with radiation of the same type and energy as the one to be monitored.

As a rule, the radiation fields to be monitored consist of mixtures of various types of radiation of different energies; occasionally they are entirely unknown. Therefore, devices have to be incorporated into the holder of the film packet, to enable one to obtain at least a rough indication of the type and energy range of the radiations involved in a potential personnel exposure and (or) to reduce the dependence of the film response on the types and energies of the radiations to within certain acceptable bounds.

3.3 THE FILM HOLDER

The film holder is usually a sturdily constructed case provided with a pin, a clamp, or another device for fastening it to the clothing, wrist, or fingers of the individual to be monitored. It should be easy to load and unload, but, at the same time, should be fairly tamper-proof.

3.3.1 X- and gamma-radiation

Most film holders in use at present contain metallic filters, covering a portion of the inserted film packets [24, 25, 26]. The filters are either of different atomic numbers or of the same atomic number but of different thicknesses, and are often positioned symmetrically in the front and back of the holders. In the energy region in which these filters absorb an appreciable amount of radiation — which is also the region of greatest energy-dependence of the film response — they cause a differentiated density pattern to be reproduced on the film. In the range in which photographic density is a linear function of exposure, the density ratios behind the different filters give an indication of the energy of the incident radiation and thus facilitate the choice of a suitable calibration curve from which the exposure may be determined.

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For many types of radiation, the layers of paper intervening between the metals and the film are not thick enough to prevent the secondary electrons produced in the metals from reaching the film. In this case, additional density differentiation may be achieved even where there is relatively little difference between the absorption of the radiation in the individual metals, particularly if the metals in the back and front of the holders are arranged asymmetrically [27].

The number of filters in the holders in use in different laboratories varies. If only one filter is used, its choice is of rather great importance, since it must reduce the energy-dependence of the selected films to within the desired limits of monitoring accuracy, and thus eliminate the need for a detailed discrimination between radiation energies [28, 29, 30]. On the other hand, although theoretically providing good discrimination between different types of radiation of different energies, a very large number of filters may become cumbersome in actual use, since intricate density patterns are confusing, particularly to the inexperienced. Also, because of the necessarily small filter-areas in the case of a large number of filters, the film areas from which information is to be obtained often become prohibitively small. This is the case particularly because scattering of the radiation from the filter edges and undercutting in the case of oblique radiation incidence may make it impossible to utilize the marginal regions of any one area.

The lower limit of usefulness of the systems so far described lies at a few mr of total exposure to X- or gamma-radiation of an energy smaller than about 0.2 MeV. For energies above 0.2 MeV, the lower limit lies at around 20 mr. A method employing scintillator screens in contact with the film emulsions may extend the useful range of the film badge down to 1 mr and less, even for photon energies above 0.2 MeV. The method is based on compensating for the decrease in the efficiency of the photographic process with increasing photon energy by an increase in the efficiency of the scintillating screen [31—35]. This method is, however, not universally applicable because of the reciprocity failure of the photographic effect caused by the visible or near-visible light from the scintillator. As a consequence, specially prepared emulsions, designed mainly to minimize reciprocity failure, and special processing techniques are often employed. Even then it is difficult to make the method useful over an unlimited range of exposure rates.

Recently, one group incorporated the scintillating material into the emulsion proper [36]. Experiments are under way to combine the

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scintillator and absorber methods, in an effort to produce a very sensitive film badge whose response is to be practically independent both of exposure-dose rate and of radiation energy [36]. At present, such a film badge is not in routine use.

3.3.2 Beta-radiation, monoenergetic electrons

The light-tight wrapping surrounding commercial films has a thickness of roughly between 2 and 25 mg/cm^2 on the front surface of the packet. A thickness of 25 mg/cm^2 stops all electrons up to an energy of close to 150 keV [37]. Thus, a film badge does not indicate the presence of these electrons. Also, close to one-half of the beta-radiation of maximum energy of around 0.7 MeV (and, of course, considerably more of the beta-radiation of lower maximum energy) is absorbed in the wrapping, and thus does not produce a photographic image. Higher-energy electrons (or beta-rays) are recorded in the so-called "open-window" area of the multi-filter X- and gamma-ray badges (i. e., in the area in which the film packet remains bare), or in the areas in which the cover consists of a thin, low-atomic-number plastic only.

In practical beta-ray monitoring procedures, the exposure geometry is usually unknown and quite variable; the type of radiation, however, (beta-ray-emitting isotopes, electrons from accelerators, etc.) is usually known. Since the beta-ray spectrum, after the filtration of the softest components by the paper of the film packet, varies only slowly with the source-to-film distance, i. e., with the thickness of the layer of intervening air, a fairly good calibration may be achieved with a standard source of the same isotopes as the ones whose beta-radiation is to be monitored; this is the case particularly if the radiation is diffusely incident.

Where the electron or beta-ray energy is entirely unknown, differential filter methods similar to those employed for X- or gamma-radiation may be used; however, the filters here should consist of thin plastic foils rather than metals. Fortunately, the sensitivity of a number of films used for the monitoring of X- and gamma-radiation does not depend appreciably on particle energy, at least in the beta-ray energy range of the most common beta-ray-emitting isotopes whose radiation penetrates the film wrapper.

3.3.3 Mixtures of X- or gamma-rays and beta-rays

A considerably more serious complication in beta-ray and electron monitoring stems from the fact that beta-ray fields hardly ever occur isolated. Even when one deals with pure beta-ray emitters, one has

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to consider the possible production of bremsstrahlung by the beta-radiation. For any given source-strength, bremsstrahlung-intensity increases sharply with the beta-ray energy, as well as with the atomic number and the mass of the matter in the immediate vicinity of the source and the mass of the source proper.*

Although the RBE of electrons and that of X- and gamma-rays are assumed to be equal, a differentiation between mixtures of these radiations is important from the biological point of view because of the difference in their penetration to vital organs. Therefore, a semi-quantitative differentiation is often attempted by means of readings in the open-window area (i. e., in the area in which the film packets remain bare) and in the film areas under the various thin aluminium and plastic filters. Yet, many experts feel that the information to be gained from film badges about beta-ray exposure in mixed radiation fields is, at best, qualitative.

3.3.4 Neutrons

The photographic effect used in the personnel dosimetry of fast neutrons is the formation of proton recoil tracks by elastic scattering of neutrons on the hydrogen in the emulsion and its immediate vicinity. It would be possible to determine the incident neutron flux from the n-p scattering cross-section and the number of proton tracks per cm^2 having a given length and direction. However, since the time and effort involved in a microscopic track analysis would be prohibitive for routine dosimetry, one simply counts the number of tracks. In a representative modern nuclear-track emulsion, a track of minimum length (i. e., consisting of three grains) is formed by neutrons of energy equal to or greater than 0.25 MeV [38]. Above this threshold energy, the requirement of neutron monitoring independent of energy can be met if the variation in the number of proton tracks can be made proportional to neutron tissue dose for all neutron energies. Since, in respect to proton-track formation (i. e., in respect to its hydrogen content), the composition of the nuclear-track emulsion, plus film base and surrounding paper layers, is quite similar to that of living tissue, it is not difficult to meet this requirement. In fact, it has been found [38] that, by establishing proton equilibrium in a laminate of paper and aluminium foil, the variation of the number of proton tracks per unit film area as a function of fast-neutron energy may be made to parallel that of the first-collision dose [20].

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* For small sources in air, low-atomic-number plastic, or soft tissue, the amount of bremsstrahlung contributing to the external dose is negligible.

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Since thermal neutrons, through the N^{14} (n_{th}, p) C^{14} reaction, also cause proton tracks in a nuclear emulsion, the mere presence of proton tracks is not in itself indicative of the presence of fast neutrons. Therefore, in mixed radiation fields, further methods of differentiation are required.

3.3.5 Neutrons in mixed radiation fields

Because of their mode of production and their high reactivity, neutrons usually occur in highly mixed fields of radiation. However, since the relative photographic effectiveness of X-, gamma-, and beta-radiation on the one hand, and of the thermal and fast neutrons on the other, is not proportional to their relative biological effectiveness, determining the film response to the sum total of these radiations is not sufficient for personnel monitoring.

The customary film holder used for the monitoring of mixed radiation fields consists of at least two metal filters of equal mass, one of cadmium and the other of tin. As a rule, both the nuclear-track film packet and the conventional gamma-ray-monitoring film packet are placed in this holder. As the (n_{th}, γ) cross-section of tin is quite small compared with that of cadmium, the density of the conventional film behind the cadmium filter is considerably higher than that behind the tin filter when thermal neutrons are present. On the other hand, in the nuclear emulsion, the number of proton tracks behind cadmium is smaller than that behind tin in the presence of thermal neutrons, because the cadmium filter shields the film from the thermal neutrons. In the absence of thermal neutrons from the radiation field to be monitored, the areas behind cadmium and tin appear alike, both on the nuclear-track film and on the conventional monitoring film. The density obtained on the conventional X- and gamma-ray-monitoring film, both by thermal neutrons in the areas not covered by metal foils of high capture cross-section and by fast neutrons, is usually negligible [39].

It may also be pointed out in this connection that, for high-energy X- or gamma-rays, even in the absence of thermal neutrons, the areas behind metallic filters will be darker than the open-window area since the action of these radiations upon the film is intensified by the electronic build-up in the metal foils. Furthermore, equal densities behind the filters and the open window can be achieved by exposure to a number of different combinations of radiations, even in the absence of thermal neutrons.

Another method of discriminating between gamma-radiation and thermal neutrons involves the use of a boron-loaded silver-activated

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zinc sulphide screen over a portion of the film surface [40]. The alpha particles produced during the capture process cause scintillations in the zinc sulphite, which, in turn, are recorded by the photographic film. The thermal-neutron dose is determined from the differences in film density behind the single metallic filter, the screen and the open-window area. Here again, the accuracy attainable is limited by reciprocity failure.

3.4 CHOICE OF EMULSIONS (FILMS)

The monitoring emulsions are selected for their uniformity and reproducibility and for their ability to cover a desired exposure range with good precision. For X- and gamma-ray monitoring, double-coated commercial X-ray film, or film singly or doubly coated with special monitoring emulsions, is used in most laboratories; at least one of the larger laboratories employs special emulsions coated on a paper base.

It usually takes two emulsions to cover the full monitoring range. For the daily routine monitoring, a range from 20 mrem to about 5 or 10 rem would be quite satisfactory; but as a rule, for the sake of full coverage in the case of an accident, an emulsion for the range from 10 to 500 rem is included as well. Some laboratories work with a special film, which is coated on one side with a sensitive emulsion and on the other with an insensitive one. For ordinary use, the exposure is determined from the net density of the complete developed film. Only when the film is too dark for evaluation, which may be the case under some conditions involving a radiation accident, is the sensitive emulsion removed after processing, the evaluation proceeding from the density of the insensitive emulsion alone. For the monitoring of fast neutrons, commercial nuclear-track films are usually employed.

Most commercial film material from reputable manufacturers is coated uniformly enough, at least on any one given batch of films, to provide for the uniformity of photographic characteristics required for personnel monitoring. For a high precision in exposure interpretation, it is further required that, at the density being measured, the density-*vs.*-exposure curve have a steep slope, i. e., that a large density increment correspond to a small exposure increment, for film processed according to prescribed methods. Also, for convenience in handling, particularly during processing, a stiff film (or paper) base is of considerable advantage.

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3.5 IDENTIFYING THE FILM AND THE HOLDER

The film packets, as well as the individual films inside, are usually marked for identification. The simplest way of marking film is by hand, with a pencil or stylus.

As a rule, numbers and (or) letters are used to identify the wearer and often also his institution and the monitoring period. A badge identification number is often perforated into the material of the metallic holder. It is then possible to transfer this number onto the film by exposing the film-loaded holder to low-energy X-radiation, shielding all but the perforated area from the radiation. Another method consists of printing numbers on both the paper of the packet and the individual films with the blunt dies of specially designed stamping machines. The dies may or may not be inked; they make their imprint on the films through the exerted pressure, without perforating the packets. Binary coding may be used to conserve space on the film surface. The printing methods are fast and convenient and lend themselves well to automation.

In institutions in which the film holder is used as an identification plaque ("badge") for the wearer, it may carry also the wearer's photograph and further identifying symbols.

Where film is not stored as part of a permanent record, an identifying portion of the film holder may remain with the film throughout all stages between exposure and evaluation, thus making film marking unnecessary [30, 40].

3.6 AVOIDING THE INFLUENCE OF LATENT-IMAGE CHANGES

3.6.1 Humidity-proofing

All calibration would be in vain if, between exposure and processing, the latent image produced in the monitoring samples were allowed to undergo changes considerably different from those in the calibration samples. The ideal arrangement would be to accumulate the calibration exposures over the entire period during which the monitoring badges are being carried and shipped, and under the same conditions of ambient temperature and humidity. This, of course, is not possible in routine personnel monitoring.

In colder parts of the temperate climatic zones, most monitoring films in present use exhibit only relatively little latent-image fading unless exposed directly to the heat of the sun or a stove, or exposed to light, water vapour or other chemical vapours, etc. Two films of the same emulsion batch, identically exposed and stored, probably will not show a difference in density of more than 10 or 15% if the one is developed immediately after exposure, while development

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is delayed on the other one for a week or two. The resulting error in exposure interpretation would be well within the limits of the overall accuracy to be expected in photographic personnel monitoring. However, in tropical or sub-tropical climates, and in parts of the temperate zone having hot, humid summers, the latent image may fade so strongly, or there may be so much fogging of the film, that an exposure interpretation may become impossible. In such climates it is necessary to use film packets enclosed by the manufacturer in humidity-proof plastic bags and to remove the films from these bags only immediately before processing, and in an air-conditioned room.

3.6.2 Precautions in storage and shipping

When not in use, both the calibration films and the monitoring films are stored at temperatures preferably between 5 and 15 °C, and at relative humidities of around 40%. Thus, while ordinary refrigerators are quite satisfactory for film that is packed in humidity-proof bags, they are to be used with caution for unprotected film. Also, care has to be taken that the films are brought to room temperature before they are distributed for use or exposed for calibration, and that they are brought to a temperature close to the processing temperature before processing. Great temperature differentials during the warming-up stage are to be avoided, since they cause detrimental water condensation on the film surfaces.

Special precautions are required to keep the monitoring and calibration films not in use away from ionizing radiation. Where it is not possible to plan for storage and processing facilities remote from radiation sources, lead or concrete protective barriers are used. Also, packages containing film should bear special shipping labels that identify the package contents and warn against the dangers of exposure to ionizing radiation.

Furthermore, unexposed control films should accompany each film shipment* from the central monitoring station to the various monitored installations. During the monitoring period, these control films remain at the institutions, but are protected from radiation. It is a good practice to keep them on the same rack on which the monitoring films are stored when not in use. They are then returned along with the rest of the films, and processed together with them. The density of the control films is an indication of possible accidental exposure during transport or storage. Control films also should be kept at the storage facility of the central monitoring station.

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* Used in the broader American sense throughout this Manual, i. e. consignments, irrespective of the mode of transport.

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3.7 PROCESSING

Unless the climate is very moderate and uniform throughout the year, all film manipulations are best carried out in an air-conditioned room or building. Processing instructions supplied with the films should be followed as closely as possible. One should avoid, in particular, developers having a tendency to produce reversal effects at high densities. This reduces the chances of ambiguity in the rare instances of accidental high exposure, and also eliminates difficulties due to reciprocity failure. As a rule, a commercial X-ray developer is satisfactory.

In order to be independent of variations in the strength and temperature of the developer used, and of small variations in processing time, all monitoring films are usually developed along with their calibration films. Although, for the reasons discussed above, it is then still necessary to follow the instructions of the manufacturer regarding developing time and temperature, the permissible variations in these factors are relatively large, and costly precise stabilization of the developing temperature becomes unnecessary; nevertheless, a certain amount of temperature control of the processing solutions is usually required.

For the simultaneous processing of large numbers of films, one requires special racks which hold the individual film samples securely and do not impede continuous access to fresh processing solution. An alternative processing method, which is used by only one personnel-monitoring station at present, is to assemble a long strip simulating cinematographic film. The individual film samples are fastened along two opposing edges to long strips of cellulose tape, fed from two reels. A little machine, specially designed for this purpose, accomplishes this task readily. Simultaneously, the film strip is rolled on drums; it may be developed like ordinary 35-mm film.* Whatever the processing method, care has to be taken to achieve uniform development. Constant agitation is the only means of insuring that fresh developing solution is brought into contact with the entire surface of each film at all times. However, when large developing racks containing several hundreds of films are used, a periodic mechanical agitation of the racks proper often results in

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* The station using this method reports that the development achieved in this way is uniform. Nevertheless, it is recommended that a laboratory wishing to adopt this method first run its own processing checks in the particular film-tank or drum it plans to use.

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eddy currents and, consequently, in streaking of the film material [3]. The best type of agitation keeps the solution in motion rather than the racks. It may be achieved by bubbling a slow stream of nitrogen through the solution [41, 42]. However, fairly good results (uniformity in density to within about 4%) may also be achieved with suitable developing racks without any agitation, if the developing solutions are stirred thoroughly immediately before the loaded racks are immersed [3].

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CHAPTER 4

REQUIREMENTS FOR SETTING UP A PHOTOGRAPHIC PERSONNEL-MONITORING SERVICE

As a rule, a group just starting a personnel-monitoring service should be in possession of just the bare minimum of basic equipment required for satisfactory operation. This insures the possibility of a gradual expansion as the needs of the particular group become apparent; with the experience of a few months (or years) of operation, adaptations may be made that, eventually, will bring about a service better suited to the individual needs of the group than could have been established by copying all the details of a service elsewhere. Nevertheless, access will have to be obtained from the start to a certain amount of equipment common to most monitoring stations. Also, adequate space will have to be provided to insure safe and smooth operation and, if possible, to take into account future expansion.

This section deals only with the main features of the basic layout and equipment required for a photographic monitoring service, but no actual specifications or sources of supply are given. The IAEA has available a selected list of laboratories in different countries, willing and able to advise institutions interested in starting such a service and to suggest suitable equipment specifications. The IAEA also is in a position to suggest suppliers of commercial equipment.

In some instances, it will be possible to make use of equipment such as X-ray machines, radioisotopes or darkrooms, usually available in the radiological departments of hospitals. The space and equipment requirements given in this section may then be reduced.

4.1 SPACE REQUIREMENTS

According to the different procedural requirements, the personnel-monitoring plant consists of several distinct areas: the *general-operations area* (or areas), providing space for film storage, badge loading, film marking (if done by pressure), densitometry, exposure evaluation and records; the *calibration area,* containing the sources and accessories required for an adequate film calibration with the

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types of radiation present in the radiation fields to be monitored, as well as a film-marking source, if films are to be identified radiographically; and the *film-processing area.* While the personnel-monitoring plant forms an organic unit, care should be taken to isolate the calibration area either through distance or through structural shielding (or both) from the other areas, so as to prevent the other areas from having, at any time, a radiation level higher than natural background.

In tropical or sub-tropical climates, and in the portions of the temperate zone having hot and humid summers, air-conditioning should be provided at least in certain portions of the area of operation. This will prevent damage to valuable equipment due to fungus infestation, insulator leakage, etc., as well as damage due to changes in the latent image during operational procedures.

4.2 EQUIPMENT REQUIREMENTS

4.2.1 General-operations area

Films and film holders

Some of the major suppliers of monitoring film have widely distributed regional branch offices. The selection of film, in addition to being influenced by the technical considerations discussed in chapter 3, will also depend on the nearest reputable commercial supply office from which film shipments can be expected to arrive regularly and within a reasonable length of time. Preferably, all films obtained for use in any one monitoring period should be from the same emulsion batch, as considerable batch-to-batch variations in film sensitivity and even in energy-dependence may exist, making it necessary to prepare a set of calibration exposures for each batch. Attention should also be paid to the expiration date appearing on the film box, which indicates the end of the period for which the film company recommends the use of a particular batch of film.

The film holder ("badge") should not be chosen independently from the films. It may be best to rely first on a combination that has proven satisfactory in a well-established laboratory of a Member State. If this is done, it may be possible either to obtain the holders commercially, or at least to obtain a pattern after which holders may be manufactured in a local shop. In either case, care should be taken that the various metallic foils incorporated into the holders are all of the same chemical composition from holder to holder and that possible variations in their thickness do not cause any appreciable error in the interpretation of low-energy X- and gamma-ray exposure.

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Refrigerator

A good refrigerator will be required for film storage. Preferably, it should be adjusted to operate above 0 °C. If the relative humidity in the refrigerator is above 40 or 50 %, open boxes of packets that were not individually moisture-proofed may have to be placed in moisture-proof bags. Unopened boxes of film, as delivered from the film distributor, can be stored without any danger in a refrigerator operating at a higher relative humidity, even if the individual film packets are not enclosed in moisture-proof bags.

Percussion press

If pressure marking is the method of choice for film identification, a percussion press either has to be obtained commercially or has to be built. Logically, the percussion press is located in the vicinity of the loading area*.

Densitometer

While in many instances the experienced eye can judge very low densities with considerable accuracy, a photometer, capable of measuring the change in film opacity with exposure, is indispensable. Most photometers in use in radiation-monitoring laboratories are photoelectric precision instruments, incorporating a stable light source, a photocell or photomultiplier, and a current measuring device. They may be used as relative indicators of opacity changes, or calibrated in terms of optical density (therefore the term "densitometer") by means of a standard density wedge; such a wedge may be supplied with the instrument, but also can be obtained from one of the larger manufacturers of photographic films.

For routine use, a photometer with a sensitivity sufficient to indicate a decrease in original light intensity by a factor of between 10^2 and 10^3 (corresponding to an optical density between 2.0 and 3.0) should be quite satisfactory. However, since the photographic method of personnel monitoring is also counted upon to give information in the important cases of accidental high exposure, a photometer indicating a light-intensity decrease of 10^5 or 10^6 (corresponding to optical densities 5.0 or 6.0) could prove a worth-while investment.

Where large voltage-fluctuations are expected in the incoming powerline, it may be necessary to operate the densitometer with a voltage-stabilizer.

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* For radiographic marking see section 4.2.2.

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Microscope

For nuclear-track counting a good microscope with a mechanical stage is required. It should be equipped with an eyepiece with scale, and a special small-depth-of-focus objective, allowing a magnification of the order of 1000 times with oil immersion.

Record storage

In order to make full use of the possibilities of the photographic method for providing a direct documentation of individual exposure, many authorities feel that all developed films should be stored in such a way as to permit future re-checks of readings in the case of medico-legal difficulties. Inasmuch as storing the personnel-monitoring films without their calibration films would be useless, it is necessary to provide such storage facilities for all developed films at the location at which the calibration films are available, i. e. in the monitoring centres. No general recommendations can be made about the film-storage period. A compromise between the desires of the monitoring service, the user, and the official authorities will have to be found in each individual instance.

The policy on how and where written records are kept of the personnel exposure depends to a considerable extent on whether a particular film-badge service is part of a governmental organization interested mainly in monitoring for the compliance with safety regulations, or a private organization, responsible both to the government and the customers. At any rate, the film-badge service should provide — preferably in duplicate — a clear statement of each individual's exposure during each monitoring period, for each type of radiation. The exposure should be expressed in absolute units that can be related readily to the maximum permissible exposure of a particular type and energy of radiation.

In order to facilitate the exposure interpretation from film density the film-badge users should supply a record of the type or types of radiation employed, and of the part of the body on which the badges are carried*. It is further desirable that the monitoring station prepare cumulative records (quarterly, annual, etc.) of personnel exposure, giving the training, occupation, age, sex, etc., of the individuals [43, 44].

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* Often, personal communication between monitoring station and user can be of additional help in explaining film-density patterns that otherwise would be difficult to interpret. This is one of the reasons why it is desirable for a monitoring station not to service laboratories too remote for ready personal contact.

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4.2.2 The calibration area

The complexity of the radiation fields to be monitored determines the complexity of the calibration facilities. The following description covers the calibration sources required for personnel monitoring around the more commonly encountered radiation fields.

X- and gamma-rays from around 30 keV to 1 MeV and above

As a rule, the routine calibration consists in establishing a density-*vs.*-exposure curve, if feasible for the radiation energy spectrum resembling the one to be monitored, or otherwise for any other energy spectrum that is readily obtainable. Furthermore, the energy-dependence of the film sensitivity should be determined, if possible, once for each emulsion batch. Ideally, this determination should be carried out with monoenergetic sources covering the energy range of interest. However, since standard monoenergetic gamma-ray sources of adequate strength are not available for the important low-energy portion of the range, one customarily employs narrow energy bands of X-radiation from commercial X-ray machines for the low-energy portion, and gamma-ray sources only for the high-energy portion of the range. One laboratory, which is particularly interested in two specific long wave-lengths, produces these wave-lengths by the X-ray fluorescence method. An X-ray machine is required for both methods. In the laboratories in which radiographic identification of the films is the method of choice, this machine may be used for the marking process as well*.

A reliable 250-kV X-ray generator having either pulsating or constant potential will usually be satisfactory. Either an industrial or a therapy-type X-ray tube may be used, the therapy tube being as a rule preferable because its larger focal spot and target angle insure a more uniform calibration beam. It should be possible to regulate both the incoming line voltage and the filament current, and there should be meters in both circuits. Where line-voltage variations greater than a few volts are to be expected, a voltage-stabilizer should be employed.

In order to isolate narrow calibration bands from the continuous X-ray spectrum, it is necessary to employ relatively heavy filtration in the X-ray beam. In selecting a suitable set of filters, one may be guided by the consideration that a particular band of X-radiation is

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* Any low-energy X-ray beam (30-kV exciting potential, or preferably less) can be used for marking. Some laboratories have a special set-up for X-ray marking; at least one uses a grenz-ray unit.

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satisfactory if, in its absorption characteristics, it behaves similarly to monoenergetic radiation.

Whether this is the case may be determined experimentally by means of absorption curves in a metal, say, in aluminium or copper. The X-ray band is satisfactory if the absorption curve produced by adding absorber materials to the filtration required for the particular band is essentially exponential; i. e., if, by adding absorber materials, the half-value layer of the emerging radiation does not change appreciably.*

The filtration required for such a band may be obtained by a number of different metal combinations in different thicknesses, as well

TABLE I [a]

PRODUCTION OF NARROW ENERGY BANDS BY MEANS OF SINGLE FILTERS

Constant exciting potential (kV)	Filtration [b] (mm)	Output [c] (mr/min at 1 m and 7.5 mA)	Approx. effective energy (keV)
40	0.5 Al	550	25
50	0.5 Al	1 040	30
60	0.83 Cu	44.6	46
70	0.83 Cu	113	48
90	1.66 Cu	140	67
100	2.16 Cu	154	74
110	3.33 Cu	116	87
120	4.94 Cu	81.5	97
130	6.26 Cu	79.4	105
140	6.26 Cu	129	110
150	7.54 Cu	132	120
160	10.12 Cu	95	130
170	12.97 Cu	69.7	130
180	12.97 Cu	102.5	140
190	15.55 Cu	85.5	150
200	15.55 Cu	121	160

[a] From reference [28].
[b] Exclusive of inherent filtration, here equivalent to 0.08 mm Cu at 170 kV.
[c] The figures in this column can be considered as representative only for the particular X-ray tube used.

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* For experimental details on how to obtain absorption curves, half-value layers, etc., see ICRU Report (1959) [4]. It is recommended that pure metals be used in order to make a comparison with the work of other laboratories possible, and so that "effective energies" can be determined (see following paragraph in text).

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TABLE II [a]

PRODUCTION OF NARROW ENERGY BANDS, MULTI-FILTER METHOD

Constant exciting potential (kV)	Filtration [b] (mm)			Approx. effective energy (keV)	Approx. half-value layer (mm Cu)
	Pb	Sn	Cu		
50	0	0	0.3	40	0.13
100	0.5	0	0	70	0.76
150	0	1.5	4.0	120	2.4
200	0.7	4.0	0.6	170	4.0
250	2.7	1.0	0.6	210	5.3

[a] With the exception of the filter used at 50 kV, the filter selection was described in detail in the literature [45]. The 0.6-mm Cu filters at the two highest energies were added later; they prevent the K X-radiation from the tin from reaching the detector. The values of "effective energy" quoted here are newer and probably better than the ones in the publication. The filters were adjusted to give similar outputs at all five calibration points, namely, around 20 mr/min at 1 m per mA of filament current.

[b] Exclusive of inherent filtration, which was equivalent to about 4.5 mm Al over the spectral range covered in this Table.

as by single filter blocks. Tables I and II give examples of how one may produce energy bands satisfactory for the calibration of film badges as well as of other radiation detectors*. The columns headed "effective energy"** give the energy of the monoenergetic radiation having similar absorption characteristics to those of the selected narrow bremsstrahlung band. If suitable metal-rolling facilities are not available locally, the metal for these or similar filters may be purchased in sheet form, already rolled to a thickness not too far from the desired optimum.

If fluorescent radiation is to be used for calibration purposes rather than the narrow bands isolated from the bremsstrahlung spectrum, a special fluorescence chamber, to be attached to the X-ray machine, has to be built [47, 48], and suitable radiators and filters have to be purchased. (See also section 5.5.1.)

For the actual film calibration, the film response to known exposure doses at one suitable energy is measured in detail, and periodic checks are made for other energies, in order to establish the batch-

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* Further examples are available in the literature [46].

** This is the customary English term; the term "énergie équivalente", used in the French original of Table I, is probably more descriptive. The concept of "effective energy" or "énergie équivalente" is meaningful only for very narrow bremsstrahlung spectra.

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to-batch agreement of the energy-dependence of the film response*. For determining the exposure doses at the film position, one requires a laboratory standard of exposure dose. Therefore, the photographic monitoring laboratory should own an ionization-chamber-type instrument with a set of chambers useful for both high and low energies, over a range from at least 1 to 20 r. The instrument is best reserved exclusively for work by the monitoring laboratory, as it may lose its calibration through rough handling. The instrument should be calibrated with radiation of energies similar to the ones for which it is actually to be used**. Its constancy should be checked periodically with a small radioactive source. A check on the voltage sensitivity of its electrometer is also desirable.

Calibration laboratories often work with constant potential rather than with pulsating generators. For this reason, even if they use the generator voltage and the beam filtration specified by the monitoring stations, their spectral bands differ somewhat from the ones produced in the monitoring stations employing pulsating potential. This is no serious shortcoming, since, for two beams having the same half-value layer, the calibrations done with constant and with pulsating potentials agree within the accuracies required of the instruments.

For the film calibration in the 1-MeV energy range, one may employ laboratory standards either of radium, of Co^{60} or of Cs^{137}***. If the activity of the source is not known exactly, the exposure-dose rate may be determined with the high-energy ionization chamber supplied with the laboratory standard of exposure dose.

Beta-radiation (electrons)

A beta-ray calibration is more readily carried out with a commercially available thick plaque of natural uranium. While such a uranium plaque cannot be considered a standard beta-ray source (it emits gamma-rays, alpha-particles, and some bremsstrahlung, as well), it represents a convenient film-calibration source that can be used in contact with the film packet or badge. Its beta-gamma sur-

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* For details on accepted calibration procedure, see ICRU Report (1959) [4].

** The IAEA is in a position to accept requests from Member States for the calibration of laboratory standards. Such calibration might be done, for instance, at laboratories suggested by the Bureau International de Poids et Mesures (BIPM) and ICRU.

*** See Appendix I of ICRU Report (1959) [4] for photon energies and specific gamma-ray emissions.

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face-dose rate behind a 7 mg^2 absorber (in thickness approximately equal to the dead layer of the skin) has been determined by several experiments [49, 50]. It may be taken to be about 225 mrad/h.

In many instances, it may be possible to obtain on loan a standard source of beta-rays whose energy spectrum is similar to the one that is to be monitored. Such a source may be used to establish the relation between the response of the particular film packets or badges to the beta-rays to be monitored and to uranium; subsequently, one may use the uranium calibration with the proper correction factor.

Neutrons

A detailed discussion of the characteristics of neutron sources available for calibration purposes is given in Table 13.1 of ICRU Report (1959) [4]. At present, the most widely used portable fast-neutron source is the Ra-Be (α, n) source, which yields about 1.5×10^7 n/sec for each curie of radium*. Like all portable neutron sources, it emits neutrons having a wide spectrum of energies. When used to expose neutron film to higher neutron doses, its high gamma-ray background interferes with proton-track counting. The Po-Be (α, n) source, which yields about 3×10^6 n/sec for each curie of polonium, has a smaller gamma-ray background, but its half-life is only around four and a half months. There is, at present, a trend to switch to Pu-Be (α, n) sources for calibration purposes. They are somewhat bulkier, but their low gamma-ray contamination and the long half-life of plutonium are definitive advantages. They yield about 1.5×10^6 n/sec for each curie of plutonium.

It may not always be necessary for a laboratory establishing a photographic neutron-monitoring service to install its own neutron source. In many instances, there may be access to already available fast- and thermal-neutron sources, in geometries suited for instrument (and film-badge) calibration. However, these sources may have to be calibrated first, or the existing calibration may have to be checked** [20]. Furthermore, in the case of monitoring for thermal

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* With the aid of this information, one can deduce by simple computation [19] that it takes about 20 hours to produce an RBE dose of 5/50 rem = 0.10 rem in a distance of 1 m from a Ra-Be source containing 1 c Ra (5 rem is the maximum permissible annual RBE dose and 50 the number of work weeks per year).

** The IAEA, in cooperation with the BIPM and ICRU, is in a position to offer advice and assistance regarding the calibration of neutron sources. See also footnote p. 35.

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neutrons, a routine film calibration with thermal neutrons is usually unnecessary. The radium, Co^{60}, or Cs^{137} gamma-ray calibration should suffice, once a relation between the thermal-neutron response and the gamma-ray response of the badge is established for the particular conditions of development.

4.2.3 The darkroom

Location and design

In its essentials, the radiation-monitoring darkroom differs only very little from the darkroom of the radiographic department of a general hospital. It should be remote or otherwise shielded from all radiation sources and should be kept at a temperature close to that of the processing solutions (20 °C). If possible, it should be readily accessible from the evaluation, record and storage areas of the personnel-monitoring group.

Information on darkroom design including all details, from proper light-locks, light-reflecting paints, darkroom illumination and ventilation to processing tanks and their temperature-controlled water supplies, film-processing holders, film dryers and storage cabinets, is available from commercial suppliers of darkroom equipment and X-ray accessories. As a rule, the personnel-monitoring darkroom need not be easily accessible to outsiders during the processing session; therefore it is possible to dispense with costly and space-consuming darkroom mazes. A simple, well-designed double-door light-lock is entirely adequate. In some instances, one single, positively light-tight door might suffice, for a start.

Film-processing holders

Personnel-monitoring films are usually processed in relatively elaborate holders, enabling one to handle simultaneously several hundred films of the size used for dental X-rays. Not all the holders in use in the various existing laboratories are commercially available. Many were assembled in laboratory shops, sometimes from smaller, commercially available dental-film-processing holders.

Film-processing tanks

Large film-processing holders necessitate relatively large tank-type processing vessels similar to those in use in radiographic darkrooms, usually of a capacity of 20 liters or more. Because of the need for temperature control, the individual solution tanks are, as a rule, submerged in a large, sink-type water vat, whose steady water supply is kept at the desired processing temperature. Since film should be washed in steadily flowing water, this water vat, if made

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large enough, may also be used for film washing. While this arrangement eliminates the need for a separate wash tank with flowing water, it is not the most desirable arrangement, because it is difficult to keep the water that circulated around the outside of the solution tank clean enough to prevent smudge deposits on the film surfaces.

If a group decides to design and build its own processing tanks, sinks, etc., it should consider the corrosive action of some of the processing chemicals, which limits the materials and construction methods acceptable for photographic processing equipment [51].

Temperature control

As pointed out earlier, no elaborate precision unit for temperature-stabilization is required, provided all films, including the calibration films, are processed simultaneously. A stabilization to within ± 1 °C should be adequate. Therefore, the thermostatic mixing valves supplied commercially with radiographic darkroom equipment are quite satisfactory. According to climatic conditions, flowing hot water or flowing refrigerated water — or both — is required for the proper operation of the valve in the desired temperature range. Hot water is usually available in the laboratory. Suitable water-cooling units are supplied commercially by the manufacturers of darkroom equipment.

Processing chemicals

As pointed out in section 3.7, the commercial X-ray developer and fixer recommended for use with the particular films are usually employed with the conventional monitoring films, and most of the time also with the nuclear-track films. Acid stop-baths and wetting agents are also commercially available. In spite of the slightly higher expense, the developing and fixing reagents are best purchased as concentrated liquids rather than in powder form. The reason is that the dust from the powders may easily contaminate working surfaces during the quite laborious mixing procedure and may cause spotting of the films, which could interfere with the determination of photographic density. If agitation of the processing chemicals through nitrogen bubbling is desired, details of the method, going beyond those given in the next chapter, may be obtained from the literature [41, 42].

Film dryer

The mode of drying may slightly affect film density, but as long as all films are dried simultaneously, this is immaterial for personnel monitoring. Any method that guarantees a clean, evenly dried film

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surface should be satisfactory. Where speed is important, a commercial dryer of the forced-air or desiccant type, or of a combination of the two types, may be of advantage. Warm-air drying is satisfactory for films having a relatively thick base. One laboratory found that films whose base material is 0.2 mm thick could be successfully dried in warm air, while films with a 0.14-mm base showed a tendency to curl, a condition leading to film losses out of the developing racks. Also, because of the possibility of dust impregnation of the wet film surfaces, home-made forced-air systems should not be used without adequate air filters. Where time permits, drying in room air is quite satisfactory.

4.3 MANPOWER REQUIREMENTS

It is rather difficult to lay down manpower requirements applying to different types of photographic monitoring laboratory, regardless of the number and types of radiations to be monitored, and regardless of the degree of automation and simplification of the various procedures. However, in general, one physicist experienced in the field of personnel monitoring should be able to handle a large department with the aid of technical assistants having some previous experience, supplemented by on-the-job training, and with the aid of clerical help. In a laboratory of a given scope, the number of persons required will depend largely on the organization and simplification of such bottle-necks as film dispatching (packing, addressing, etc.) and the recording and reporting of results.

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CHAPTER 5

EXAMPLES OF PHOTOGRAPHIC PERSONNEL-MONITORING PROCEDURES

The existing photographic personnel-monitoring services may be classified from several points of view. Probably the most important classification categories are the type of the monitoring laboratory and the type of film badge used.

Types of monitoring laboratory:

(1) Medical, industrial, or research laboratories, using relatively small amounts of radium, radioisotopes, and bremsstrahlung sources, but no sources of neutrons; and

(2) Atomic reactor plants or other laboratories using relatively strong sources of all types of ionizing radiation.

Types of film badge used:

(a) Single-filter badges with or without open window;

(b) Multi-filter badges with open window, either with all filters of the same material, or with filters of different materials;

(c) Badges utilizing primarily the electron emission of metal foils rather than their absorption; and

(d) Fluorescent-radiator badges.

The two sub-divisions of the first group may be combined with each of the four sub-divisions of the second group; the result is eight combinations. Examples will be given for the combination classes that are in most general use at present, and, whenever possible, references from which further details may be obtained. A particular monitoring station may handle laboratories in both sub-divisions of the first grouping and may use more than one type of badge (i. e. may fall only into one or into two categories of the second grouping). All monitoring stations whose services are described are among those having expressed their willingness to give assistance in establishing new services and to provide, upon request, at least temporary personnel monitoring to installations in Member States.

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The description of the services is never complete. In fact, in certain instances, only some noteworthy phases are covered, in which the particular service differs from the majority of other services. In general, the relatively simpler services, which are reviewed first, are described in greater detail than the more elaborate ones. No further mention is made of the additional routine personnel-monitoring equipment in use, such as ionization-chamber-type pocket dosimeters, which, as a rule, are used to supplement the film-badge service. Finger-ring badges, wrist-type badges, etc., are not described separately, as they usually are adaptations of the routine chest badge, modified for the specific use.

In general, it would not be wise for a laboratory planning to establish a photographic personnel-monitoring service to copy any one particular existing service completely. Nevertheless, the examples of existing services given in this section may prove useful as guides for selecting one or the other suitable detail. The resulting method may turn out to be an entirely new compromise, in which existing procedures are adapted to the needs of a particular group.

5.1 CLASS 1-a [23, 28, 30]

5.1.1 First example

Film holder. Commercially available lidless lead box, 1 mm wall thickness; a filter, consisting of 0.2 mm lead and 0.7 mm tin, and again 0.2 mm lead, fits into the box.

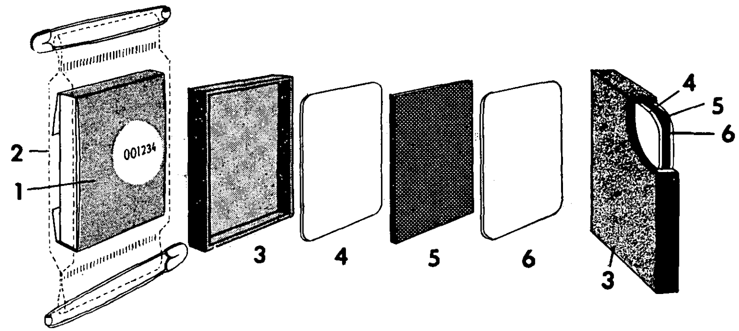

Fig. 1

Example 5.1.1; film badge and its assembly
1 — Paper cover with identification number; 2 — Plastic tubing; 3 — Lead box (1 mm lead); 4 — Kodirex film packet; 5 — 0.2 mm Pb + 0.7 mm Sn + 0.2 mm Pb; 6 — Kodak type M film packet.

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Films. Types M and Kodirex, made by Kodak*, regular dental-size packets (about 3 × 4 cm).

Film-badge assembly. (See also Fig. 1.) The sensitive Kodirex film is placed at the bottom of the lead box and the filter assembly on top of it; the insensitive type-M film lies on top of the filter.

Badge identification. Both the holder and the films are numbered, the films with the aid of a punching press.

Calibration. The film response is determined as a function of photon energy; filtered bremsstrahlung is used as well as Co^{60} gamma-radiation. A full characteristic curve is obtained with X-rays produced at 60 kV constant exciting potential. During irradiation, the badge is backed up with a sheet of plastic, simulating the human body, and is rotated about an axis perpendicular to the direction of the incident radiation, so that the angle of incidence of the radiation on the film surface varies between 0 and 180 degrees. This decreases the error due to the rather high direction-dependence of the response of film exposed in this particular holder.

Processing. The thermostatically controlled developing bath is agitated mechanically for about half an hour before receiving the developing rack. During development the rack is manually agitated. The monitoring films are developed together with unexposed controls furnishing background density, and with a set of exposed processing controls, with which the constancy of the developing solution is checked. When not in use, the developer is protected from the influence of oxygen by a floating lid. After three weeks or 5000 cm^2 of developed film per 5 l solution (whichever of the two occurs earlier), the developer is discarded. Every time a new developing batch is started, a complete set of calibration films is developed along with the monitoring films and the processing controls.

Evaluation. The sum of the net densities of the sensitive and insensitive films is determined. A calibration curve of density-*vs.*-exposure is plotted, from which the exposure corresponding to the sum-densities may be read off immediately, without any knowledge of photon energy. Fig. 2 shows the degree of compensation of the energy-dependence of the film response which makes this procedure

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* Kodak manufactures films in the United States of America, England and France (Kodak-Pathé); films of the same type-designation made in the different plants are similar, though not identical in their characteristics. Also, similar films may have different designations in different countries; for instance, the English type Kodirex is similar to the American type KK.

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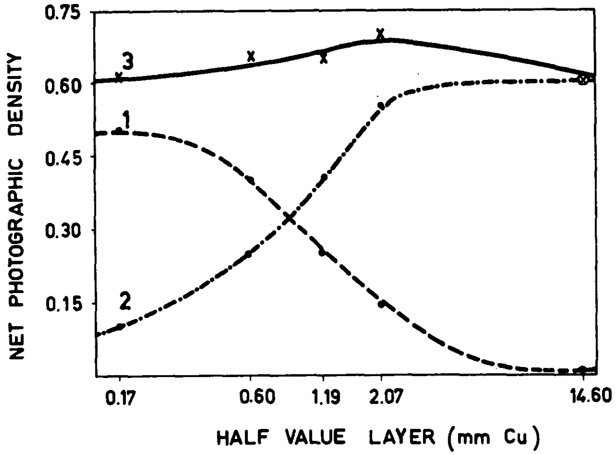

Fig. 2

Example 5.1.1; degree of compensation of the energy-dependence of the film response

The data were obtained under perpendicular radiation incidence.

1 — Kodak film type M only; 2 — Kodak film type Kodirex only; 3 — Sum response.

feasible. Where it seems desirable, one also plots sensitivity curves for the two films densitometered separately. One then obtains an indication of photon energy from the ratio of the densities of the sensitive and insensitive films.

Exposure record. A record card is sent out to the individual users of the service. It is made the responsibility of the user to record the details of exposure, film number and film position at the end of each monitoring period. The cards remain the personal property of the users.

Monitoring period. Two or four weeks, according to mutual agreement between service and user.

Exposure range monitored. From 0.020 to 1.0 r over the photon energy range from 0.025 to 2 MeV or more.

5.1.2 Second example

Film holder. Two sheets of tin, 2 mm thick, a hole perforated in one corner, 0.025 mm aluminium foil, polyvinyl tubing, 0.3 mm thick.

Films. Ilford types N 550 and PM 2, cut to size 15 × 20 mm.

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Film-badge assembly. (See also Fig. 3.) The films are cut to the correct size and wrapped in paper. The packet containing the more sensitive film type PM 2 is sandwiched between the two sheets of tin foil. The packet containing the less sensitive film type N 550 is placed on top of the assembly, which is then wrapped in the aluminium foil and inserted into the polyvinyl tube, together with a numbered paper tab. Finally, the tube is sealed.

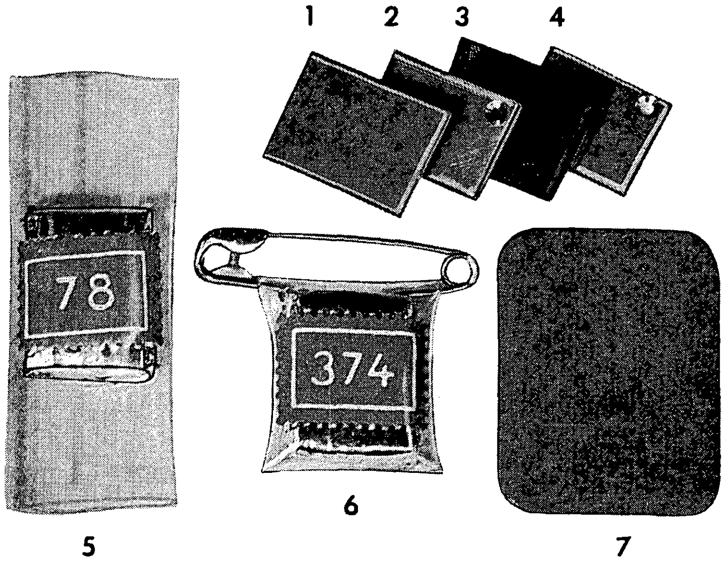

Fig. 3

Example 5.1.2; film badge

1 — Ilford N 550 film packet; 2 — 2 mm tin; 3 — Ilford PM 2 film packet; 4 — 2 mm tin; 5 — Components (1) to (4), wrapped in 0.025 mm aluminium foil and inserted into a 0.3-mm polyvinyl tube; 6 — Complete package; 7 — For comparison only: dental film, normal size.

Badge identification. The paper tab carries the number of the user and of the monitoring period. The films themselves are not numbered. The hole in the tin filter aids in the discrimination between the sensitive and the insensitive film, since it produces a darker dot on the sensitive film when the badge is exposed to low-energy radiation.

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Calibration. One set of films is given a fixed exposure (0.4 r) at different radiation energies, using filtered X-rays produced at constant exciting potentials between 50 and 250 kV, as well as Cs^{137} and Co^{60}-gamma radiation. This exposure series yields curves of badge response as a function of (effective) photon energy. Another set is given a series of different exposures at a fixed radiation quality (150 kV constant exciting potential, added filtration: 1.0 mm aluminium and 0.5 mm copper). This set yields a density-*vs*.-exposure curve for the evaluation of the exposure received by the monitoring samples.

Processing. All calibration films, monitoring films and environmental controls are developed simultaneously. Upon their return from the monitoring stations the film packets are immediately placed in compartments carrying the same numbers as the packets. These compartments are used both as film-processing holders and for convenient storage of the exposed film packets and films during

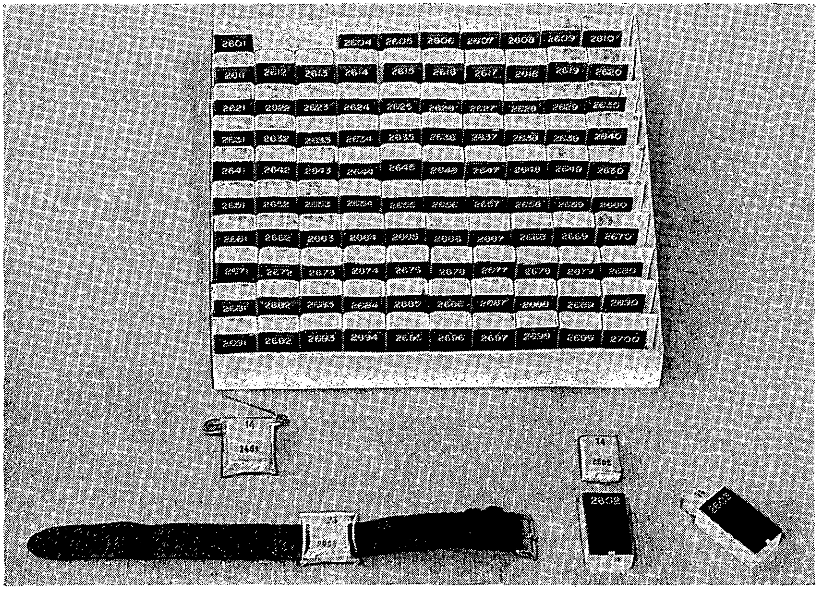

Fig. 4

Example 5.1.2

Compartments for storage and processing of exposed film packets and films

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manipulation (Fig. 4). This reduces the likelihood of confusing the film samples in the darkroom, where they are unwrapped one by one and replaced into their own compartments. All calibration films, monitoring films and environmental controls are developed simultaneously in a special tray which can carry about 1600 numbered compartments.

Evaluation. The sums of the net densities are determined. If the sum-density is greater than 0.5, the films are also densitometered separately. (This, along with the hole in the tin filters, facilitates conclusions regarding radiation energy.) The further evaluation proceeds as described in section 5.1.1.

Exposure record. Record cards are kept by the monitoring laboratory for an indefinite period of time. The films themselves are not stored.

Monitoring period. Two weeks.

Exposure range monitored. From 0.020 r to 4.0 r of X- and gamma-radiation of photon energies between 0.03 and at least 1.25 MeV. This range can be extended to approximately 40 r by measuring the silver content of the films by means of quantitative X-ray fluorescence analysis.

5.1.3 Third example

This is a service falling into both classes 1-a and 2-b. The portion falling into class 1-a is quite similar to the first service described under 1-a, except that it is carried out for low-energy X-radiation only. The portion falling into class 2-b is similar to other services described in that class and therefore is not mentioned any further. An interesting detail is the use of differently coloured badges for successive monitoring periods, and also for different types of radiation (X-ray badges, gamma-ray badges, gamma-ray and neutron badges, etc.).

Also, the practice of supplying the new customers with two badges, the one to be worn on the coat lapel, the other one on the sleeve, may be worth mentioning. Once the habits of a particular customer are known, only one badge is supplied which then is worn on the one of these two locations that was found more likely to receive the higher radiation exposures.

5.2 CLASS 1-b [33, 52—61]

5.2.1. First example

Film holder. The film holder consists of one piece of 0.5-mm aluminium sheet formed so as to enclose the filter and the film packet.

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The front of the aluminium holder leaves one-fourth of the inserted film packet uncovered (see Fig. 5). The filter assembly which slips loosely into this holder consists of a sheet of lead 0.5 mm thick, bent so as to line about one-fourth of its front and the entire back of the aluminium holder; and of a sheet of copper, 0.5 mm thick, bent so as to line one-half of the front and one-fourth of the back of the aluminium holder. By this design both the differential absorption properties of the metals and their differential electron emission are utilized; the latter is of importance mainly for high-energy radiation.

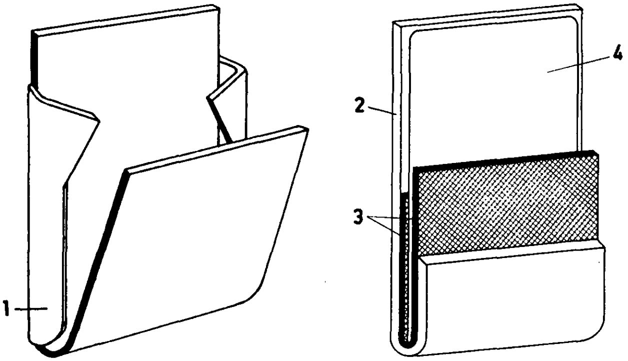

Fig. 5

Example 5.2.1; film badge

1 — 0.5 mm aluminium holder; 2 — 0.5 mm lead; 3 — 0.5 mm copper; 4 — Film packet.

[Components (2), (3) and (4) are inserted into (1); the front of one-fourth of the film packet remains uncovered.]

Film. Kodak Ultra-Speed periapical dental X-ray film packet, type DF-58.

Film-badge assembly. The film packet is slipped into the holder between the filters.

Badge identification. The film packets and films are numbered through pressure by means of a punch machine which stamps a five-digit serial number on each film, identifying the monitoring station, the department, and the individual monitored.

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Calibration. Characteristic curves are established for X- and gamma-radiation of various qualities, including radium gamma-rays and X-radiation of the following characteristics:

Constant exciting potential (kV)	*Added filtration* (mm)	*Half-value layer* (mm)
50	1.5 Al	1.6 Al
75	2.5 Al	2.5 Al
175	0.5 Cu + 1 Al	0.9 Cu

The inherent filtration of the X-ray tube is 1.5 mm Be.

Processing. All calibration and monitoring films are developed simultaneously by conventional time-temperature techniques. Seven commercially available dental-film developing racks, supported by a common frame, make it possible to develop 100 films simultaneously.

Evaluation. The proper density-*vs.*-exposure curve is selected on the basis of the density ratios on the monitoring film. Films exposed to both low- and high-energy radiations are evaluated by first determining the high-energy contribution as indicated by the density under the lead portion of the film.

Exposure record. A special record form is submitted in duplicate by the department requesting the monitoring service. After evaluation of the exposures, one copy of the completed form is returned; the original is kept by the monitoring service. A cumulative exposure record is maintained for each individual monitored.

Monitoring period. One month.

Exposure range monitored. From 0.020 to 2.0 r.

5.2.2 Second example

Film holder. (See Fig. 6.) Plastic holder, with snap-fit closure, having an open-window area, a 0.5-mm lead filter and a 0.12-mm copper filter, both in front and in back.

Film. DuPont film packet type 545, containing film type 555.

Badge identification. Through pressure marking, visible on both the packet and the film. The first two digits represent the wearing period and the remaining five are film serial numbers. The wearer prints

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his name on the packet. No attempt is made to issue the same number to a wearer each period; however, each period the names and numbers are reported to the service for cross-referencing.

Calibration. Sets of films are exposed to filtered X-radiation and to radium-gamma rays.

Processing. The customary time-temperature procedure is used, with occasional manual agitation. A 2% acetic-acid stop-bath is employed between developing and fixing baths and a wetting agent before drying. Special developing racks are employed, each containing close to 500 films. (See Fig. 7.) Two such racks may be run through the processing solutions simultaneously. A complete set of calibration films as well as unexposed control films are processed with each rack.

Evaluation. Plots are prepared of lead-absorber density *vs.* open-window density for the various X- or gamma-ray exposure conditions (Fig. 8), as well as of the corresponding characteristic curves for the open-window area (Fig. 9). With the aid of the first plot, the exposure condition of the calibration films most closely resembling that of a particular monitoring film is determined from the ratio of the density under lead and in the open-window area. The X- or gamma-ray exposure to the monitoring film can then be determined from the properly selected calibration curve of the second plot.

Occasionally, exposures to beta-rays are detected by a markedly high open-window density, in the absence of an appreciable density under the copper filter. In this case, the ratios of the densities under lead

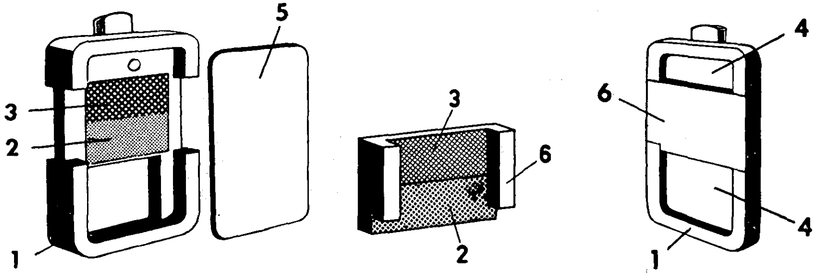

Fig. 6

Example 5.2.2; film badge

1 — Film holder (plastic); 2 — 0.5 mm lead; 3 — 0.12 mm copper; 4 — Open window; 5 — Film packet; 6 — Plastic lid snapping into position as shown in the assembled badge.

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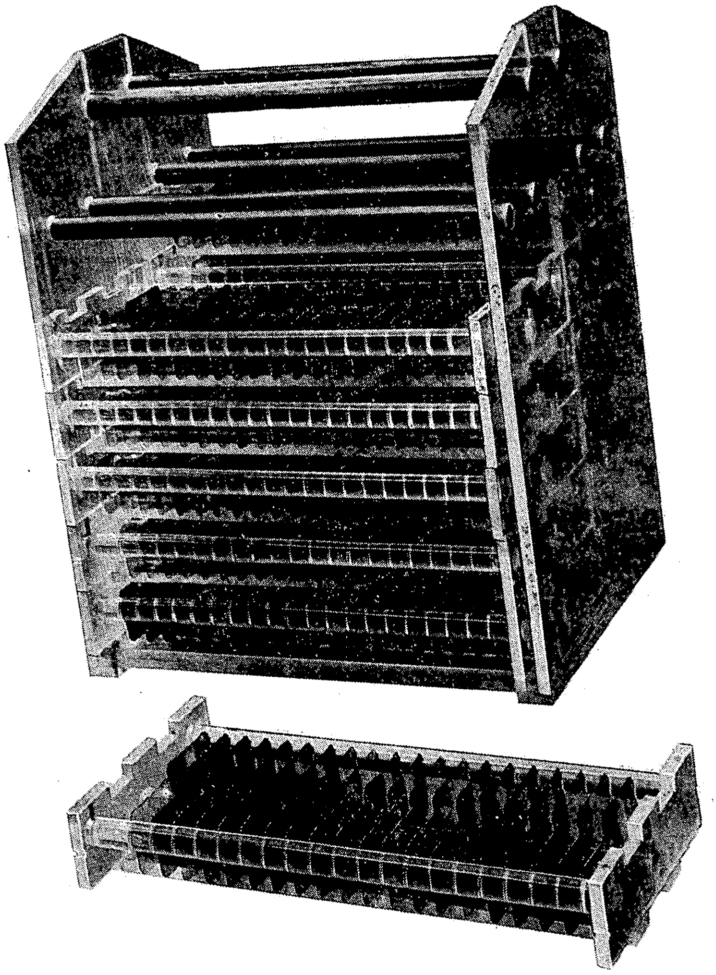

Fig. 7

Example 5.2.2
Film processing rack

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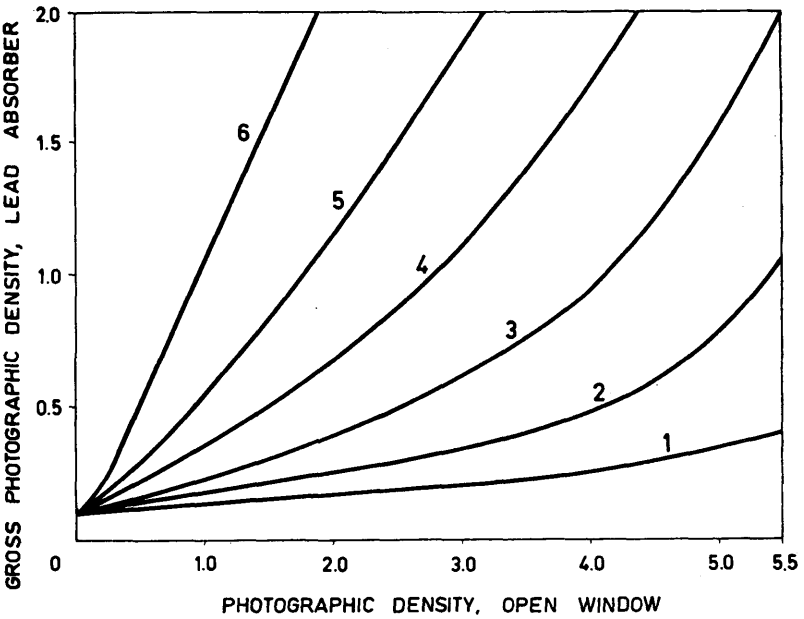

Fig. 8

Example 5.2.2; relationship between photographic density behind lead absorber and at open window, obtained with different radiation qualities

Curve designation	*Half-value layer* (mm Cu)	*Constant exciting potential* (kV)
1	0.13	70
2	0.23	130
3	0.51	150
4	1.45	200
5	2.05	250
6	radium-gamma rays	

and copper are used for the determination of X- or gamma-radiation quality, and a notation is made on the report about the presence of beta-radiation.

Exposure records. Bi-weekly exposure reports are issued. Also, a punched-card record is maintained for each subscriber, allowing the classification of the recorded exposures by the monitored individuals' age, sex and occupation, and by the location of the badge on the

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body or the extremities. At the end of each year, the cumulative exposure is determined and the cards are punched in one of seven cumulative-exposure-range categories.

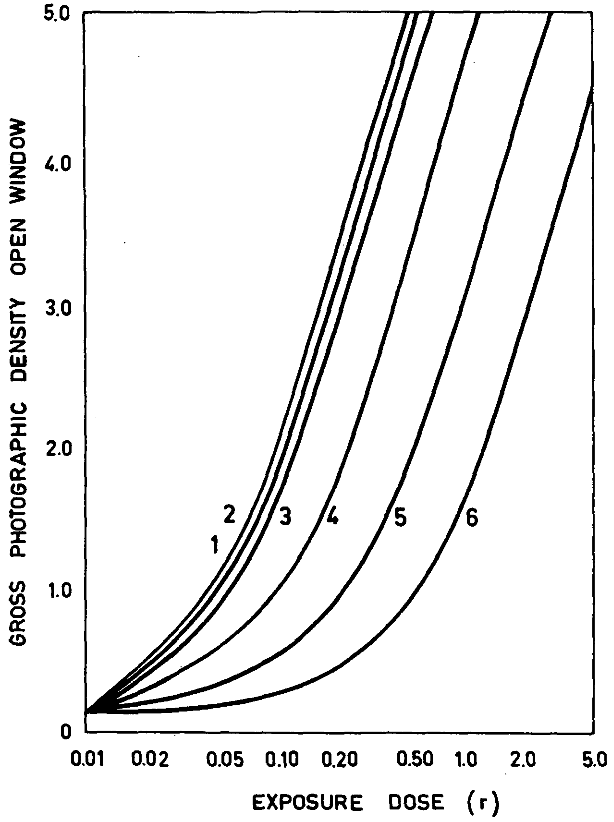

Fig. 9

Example 5.2.2

Characteristic curves for open-window area, obtained with different radiation qualities

(Curve designation: same as in Fig. 8.)

Monitoring period. Two weeks.

Exposure range monitored. From 0.040 to 20 r of radium gamma-radiation, and of X-radiation, starting with radiation generated at

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70 kV constant exciting potential (HVL: 0.13 mm copper), and going up to radiation generated at 250 kV constant exciting potential (HVL: 2.05 mm copper).

5.3 CLASS 1-c [27]

5.3.1 Example

Film holder. Front lid of 1.5 mm brass, with circular aperture in the centre. Steel back, 0.6 mm thick, lined with a 0.1-mm lead foil along three-quarters of its length, with an oblong slit cut across the centre, intersecting the circular aperture in the front lid, when the lid is in position. (See Fig. 10 for details.)

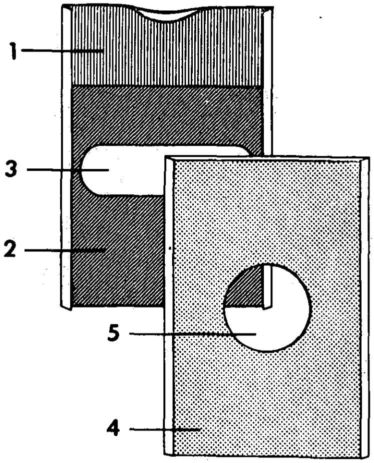

Fig. 10*

Example 5.3.1; film badge

1 — 0.6 mm steel; 2 — 0.1 mm lead over 0.6 mm steel; 3 — Open slot; 4 — 1.5 mm brass; 5 — Circular aperture.

Film. Ilford PM-1 film packet.

Film-badge assembly. Front and back portions slide shut along narrow guides, sandwiching the film in-between. Note that the

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* From ref. [27], used by permission of the Editors of the British Journal of Radiology.

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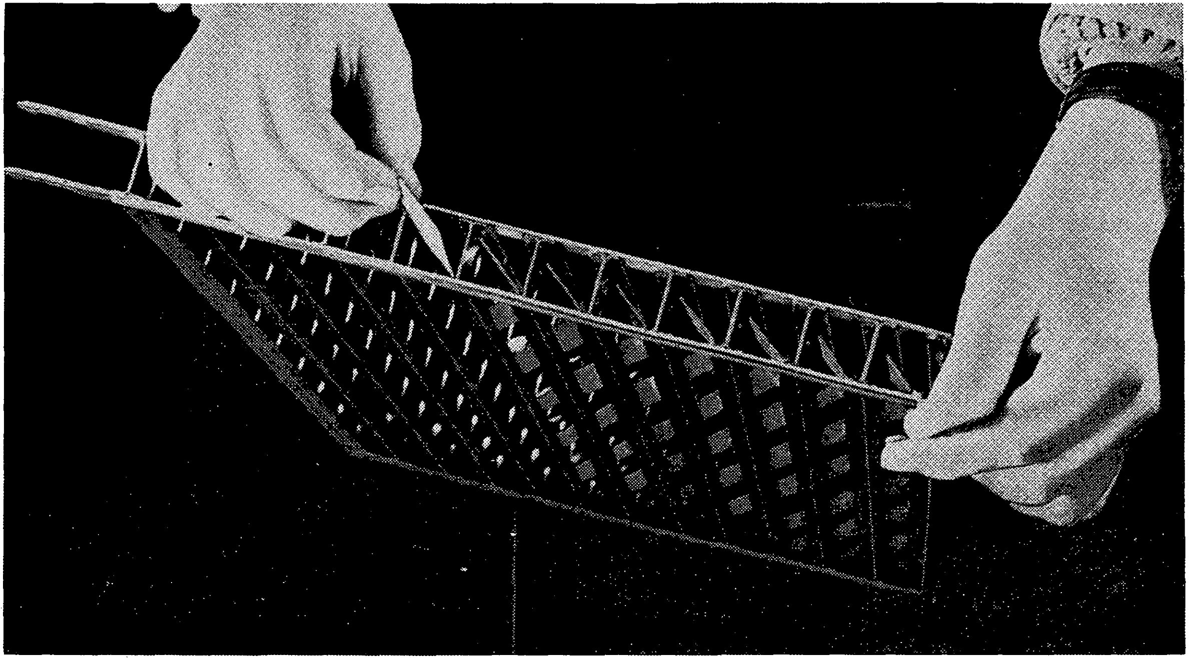

Fig. 11*

Example 5.3.1

Loading of the processing rack

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* From ref. [26].

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electron-emission method here employed works with any single-film packet in which the area density of the paper wrapping in contact with the lead foil does not significantly exceed 200 mg/cm^2. In the case of the Ilford PM-1 film the packet is accommodated in the holder with the thinner wrapping facing the lead-lined back.

Badge identification. Each film holder carries a number engraved on the front lid. This is the number permanently allotted to each monitored individual. The wrapped films are numbered by means of a commercial, hand-operated percussion press, having a six-digit numbering head. There are two sets of holders having different colour codes, which are distributed in successive monitoring periods.

Calibration. The routine calibration is carried out on bare film packets, with X-radiation at an exciting potential of 100 kV and with a 1.5-mm copper filter added to the inherent filtration equivalent to 1 mm Al. Also, an occasional check is made with a calibrated radium source. The energy-dependence of the film response was obtained at the time the present method of monitoring was adopted. Because of the reproducibility of the energy-dependence from emulsion batch to emulsion batch, regular re-checking of the energy-dependence was found to be unnecessary.

Processing. All calibration and monitoring films are processed simultaneously by conventional methods. A commercially available processing rack holding close to 150 films is used (Fig. 11).

Evaluation. A photographic density-*vs.*-exposure curve is plotted from the data obtained at 100 kV exciting potential. Corresponding curves of the responses as a function of energy are prepared, from which the correction factors are obtained that are used to relate the dose interpretation at any desired radiation quality to that obtained from the density-*vs.*-exposure curve for diagnostic X-radiation. Criteria for the determination of radiation quality, and thus for the selection of the proper correction factors, are provided by the visual appearance of the pattern on the exposed film (see Figs. 12 and 13 for further details and explanations).

Exposure record. Exposure information is kept, along with information on the blood picture.

Monitoring period. One week.

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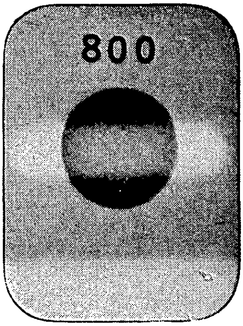

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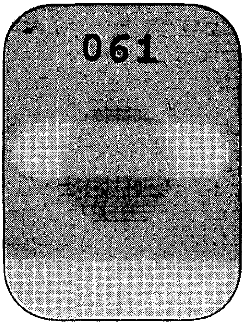

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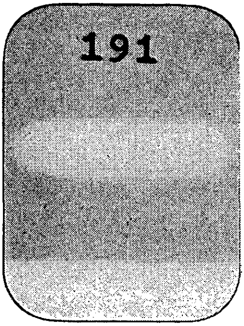

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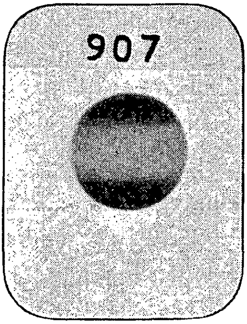

4

Fig. 12*

Example 5.3.1

Patterns on exposed films

1 — Exposed to Na^{24}; 2 — Exposed to radium; 3 — Exposed to radium, heavily filtered; 4 — Exposed to Sr^{90}.
[High energy is reliably indicated by negative contrast of backing slot and by steel causing less density than lead. Aperture contrast in (1) and (2) is misleading and is non-existent in (3).]

Exposure range monitored:

DIAGNOSTIC X-RAYS	0.002	to	1.0 r
SCATTERED RADIATION from 250-kV therapy X-rays	0.005 mr	to	2.0 r
GAMMA-RAYS from radium and radioactive isotopes	0.015	to	13 r
BETA-RADIATION	0.015	to	13 r

5.4 CLASS 2-a

In this class will be found only laboratories that rely to a relatively small extent on personnel monitoring with photographic film, sup-

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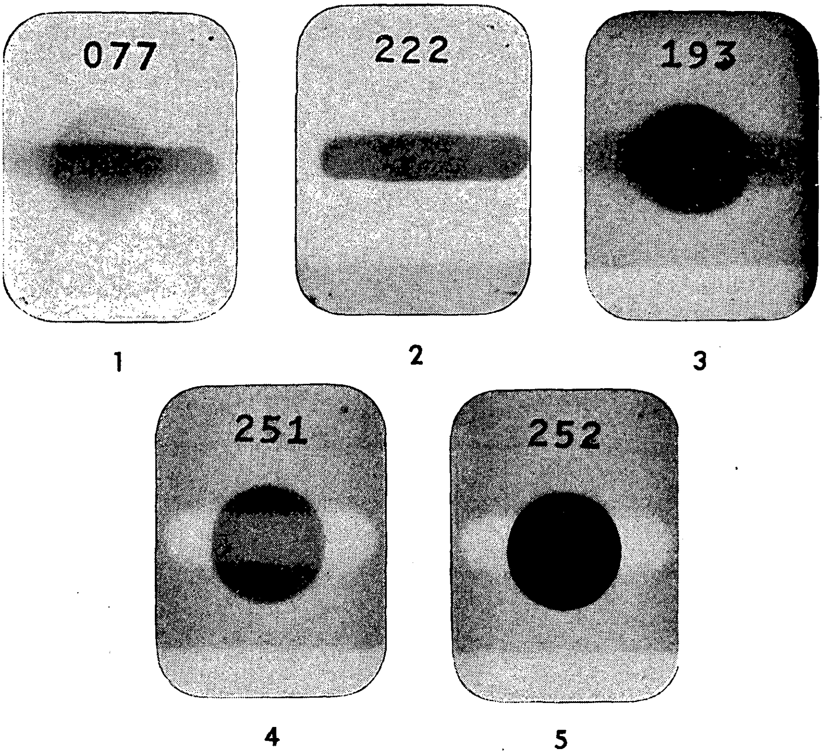

Fig. 13*
Example 5.3.1
Patterns on exposed films

1 — Film worn by diagnostic radiographer (appearance of film typical of diagnostic scatter: dark back-slot image, lead-steel border not visible, unsharp aperture); 2 — Film worn by therapist (area over steel has larger density than that over lead, a sign of therapy-scatter); 3 — Film worn by diagnostic radiographer exposed to diagnostic scatter and to patients with radium insertions (dark slot is evidence of low energy and steel-lead contrast of gamma-ray exposure); 4 — Typical radium exposure for comparison with (3) and (5); 5 — Mixture of gamma- and direct diagnostic X-rays (diagnostic component is suggested by high definition of aperture edge and low slot-aperture contrast).

plementing it rather extensively with area surveys as well as with other personnel-monitoring devices. Such devices are designed particularly to give quick and reliable information about massive

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fast- and thermal-neutron exposures, as well as massive gamma-ray exposures, such as may occur, for instance, in criticality accidents around reactors. Substances exhibiting specific neutron threshold or resonance reactions are used in foil or pellet form for the determination of neutron fluxes and neutron energies [62]. Silver-activated phosphate glass is a handy indicator of massive gamma-ray fluxes* [63].

5.4.1 Example

Film holder. A sheet of cadmium, 1 mm thick, a 0.18-mm plastic sleeve to cover the film packet; an aluminium carrying case with open front (Fig. 14).

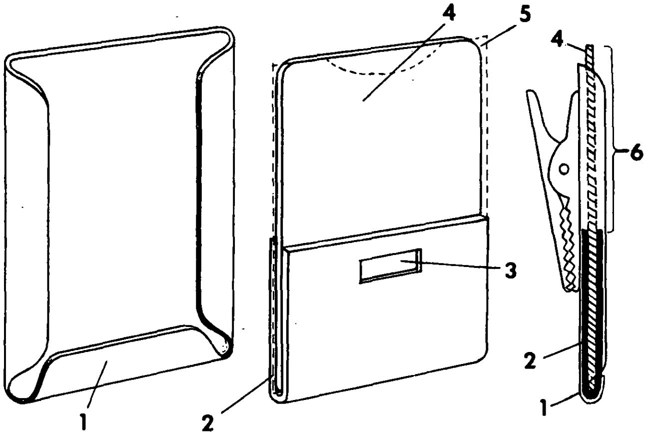

Fig. 14

Example 5.4.1; film badge

1 — Duraluminium holder (0.48 mm); 2 — 1 mm cadmium (backed by 0.48 mm duraluminium from holder); 3 — Slot in cadmium filter for ease of disassembling; 4 — Film packet; 5 — Plastic sleeve (0.18 mm); 6 — Open window.

[Components (2), (4) and (5) are inserted in (1).]

Films. DuPont film packet type 544, containing the film types 555 and 845.

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* Such devices may also be incorporated right into film badges. A picture of such a film badge is shown in Fig. 23, p. 72.

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Film-badge assembly. The sheet of cadmium is bent in such a way that it snap-fits, both in front and back, over one-half of the film packet, which is contained in the plastic sleeve. The whole assembly slides into the carrying case.

Badge identification. Before issue the badges are serially stamped on the wrapper with the employee-identity number and are also dated. After collection the emulsions are stamped with the same date and the identity number is written in in pencil.

Calibration. With Co^{60}-gamma radiation. The energy-dependence of the film response is checked with a number of different energy bands of X-radiation.

Processing. Usual time-temperature procedure. Commercially available multiple-layer developing racks are used, which hold over 500

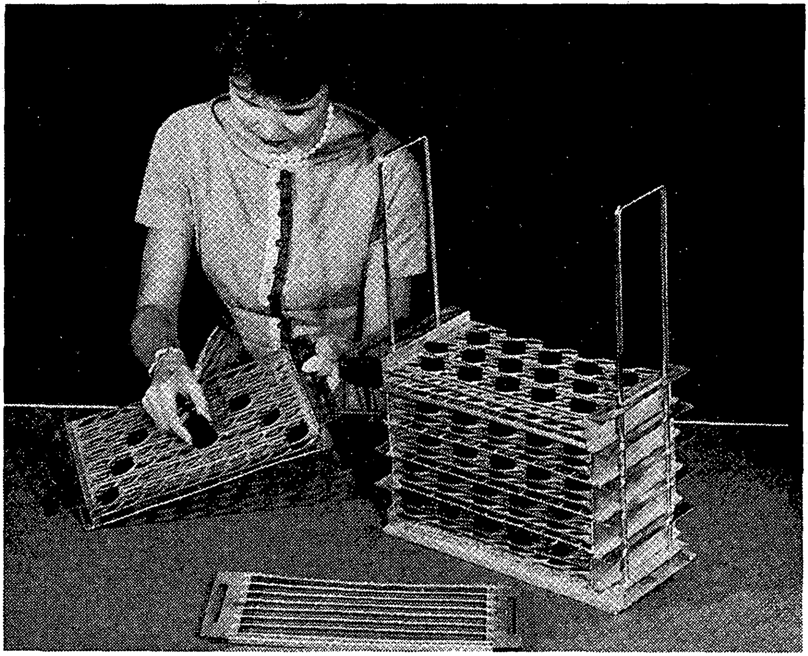

Fig. 15
Example 5.4.1
Processing rack

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individual films (see Fig. 15). The racks are not agitated during processing.

Evaluation. The exposure is determined from the density under the cadmium filter. Checks have shown agreement in most cases to within 20 % between ion-chamber readings and the exposure interpretations from the film badge obtained in this way.

An unusual feature of the service is the visual sorting method replacing densitometry for films having only background density. All processed films are spread on a sheet of white paper, and those having a density above background are selected visually. In this procedure, the operator relies to a certain extent on the recognition of the abrupt density change occurring at the location underneath the filter edge in films that had been exposed. A laboratory experiment indicated that an experienced operator was able to sort, by this method, films exposed to between 0 and 50 mr to within the accuracy of a densitometer.

Exposure record. Exposure reports are prepared listing the exposures greater or equal to 20 mr received during the bi-weekly monitoring periods, as well as quarterly and calendar-year exposures, and running lifetime totals. A simple system using IBM accounting procedures was developed for this purpose. Every worker receiving an exposure of 20 mr or more in any one period is sent a postcard informing him of the exposure.

Monitoring period. The routine monitoring period is two weeks; however, workers regularly receiving relatively high exposures are monitored on a weekly basis.

Exposure range monitored. From 0.020 to 500 r for photon energies above 50 keV.

5.5 CLASS 2-b [23, 26, 38, 41, 64—71]

5.5.1 First example

Film holder for beta-, X- and gamma-ray monitoring. Plastic case, containing an open-window area, a leaded area for marking purposes, and three filters: 1.0 mm Ag, 0.13 mm Ag, and 0.49 mm Al (Fig. 16).

The thin silver shield and the aluminium shield are equal in mass per unit area (about 0.3 g/cm^2) and thus are essentially beta-equivalent.

Film holder for X-, gamma-ray and neutron monitoring. Plastic case, containing an open window, and two filters: 1.0 mm cadmium and 1.0 mm tin.

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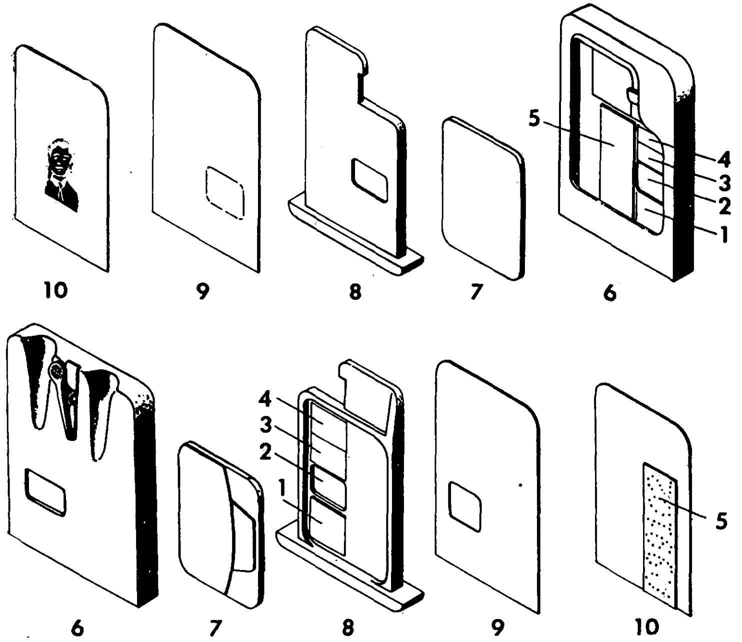

Fig. 16

Example 5.5.1; film badge

1 — 1.0 mm silver; 2 — Open window; 3 — 0.13 mm silver; 4 — 0.49 mm aluminium; 5 — 0.14 mm lead; 6 — Main body of badge holding set of back filters; 7 — Film packet; 8 — Insert holding set of front filters; 9 — Plastic sleeve for 10; 10 — Identification insert.

Films. DuPont film packet type 558, containing the film types 508 and 510; Kodak Personal Neutron Monitoring film, type A.

Film-badge assembly. Identical shielding is provided in front and back of the film packet. The back portion of the badge is secured to the main body of the badge by means of a magnetic lock. This makes the badge "tamper-proof" and, at the same time, makes it possible to load and unload the badge automatically. The lead tape next to the filters is used for radiographic film identification. A photograph and other pertinent information identifying the wearer of the badge fit onto the badge front.

Badge identification. One letter (for the location) and five digits (for the payroll number) are perforated into the lead tape and are

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radiographed onto the film with grenz-rays from a unit operated intermittently ($1^1/_2$ seconds on, $3^1/_2$ seconds off) at 12.5 kV (peak) and 12.5 mA. An additional binary-code notching system is used to designate the week and the year.

Calibration. Full characteristic curves are obtained with a rotating source of radium gamma-radiation, and, for use around plutonium, also with K-fluorescence radiation from zirconium (16 keV) and tantalum (59 keV). A calibrated PuF_4 source is used for the calibration of the nuclear-track film. Routinely, films are not calibrated with thermal neutrons; the radium-gamma-ray calibration is used instead, supplemented by the experimentally determined relation between the films' thermal-neutron and gamma-ray response. A uranium plaque is used for the beta-ray calibration.

Processing. Completely automatic film-processing equipment is used, in which a chain drive and pneumatic arms automatically transport the film racks through all processing steps, including drying (see Fig. 17 for a picture of the racks). Built-in precision-timing mechanisms and temperature control are part of the system. An acid stop-bath is used between developer and fixer. The solutions are used for one month. The developer is replenished by restoring its original volume with ordinary fresh developing solution once a week. The developing solution is agitated by a one-second nitrogen burst emitted every 15 seconds from coiled tubing in the bottom of the tank. Air is used in the same manner to agitate the stop-bath and the fixing solution. The dryer is of the forced-air type.

Calibration films, monitoring films and unexposed control films are developed simultaneously.

Evaluation. The evaluation of X- and gamma-ray exposure is done with the aid of an electronic computer. Under a number of simplifying assumptions (e. g. that no beta-radiation is received by films exposed to low-energy X- or gamma-rays, that 16-keV radiation will not produce a density under either of the silver shields, that 60-keV radiation will not produce a density behind the thick silver shield, etc.), three simultaneous equations are set up that relate the densities in the three film areas (open window, thin and thick silver shields) to the exposures equivalent to radium gamma-radiation, and to 16-keV and 60-keV X-rays. The coefficients are the slopes of the density-*vs.*-exposure curves for the three types of radiation, and are known from the calibration data. The equations are then solved for the exposures with the aid of the experimentally determined density values.

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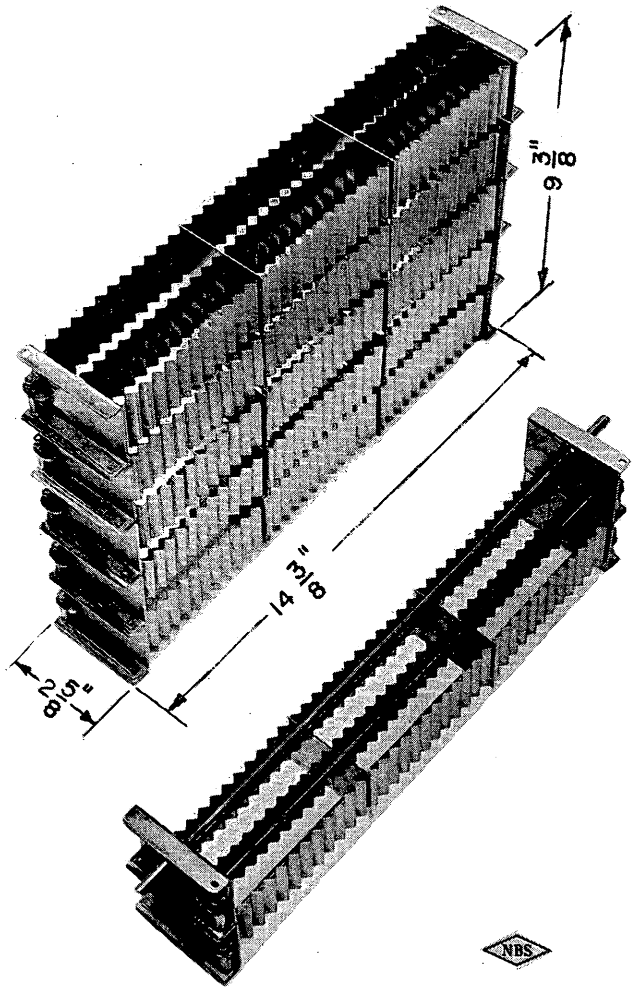

Fig. 17
Example 5.5.1
Processing rack

Exposures to neutrons of energies greater than 0.8 MeV are evaluated by having each of three observers count under the micro-

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scope the number of proton recoil tracks in 40 fields of view (i. e. in an area of 0.31 cm^2), under a magnification of 970 (oil immersion). Films indicating a significant increase in the number of tracks relative to background are examined in a total of 400 fields. The upper limit of the counts in a 90 % confidence interval is compared with the lower limit in a similar interval obtained with 300 mrem on the same area of the calibration films. (The average film response yields 71.24 ± 13.51 tracks per 40 fields of view, equivalent to 1075 mrem, with a 95 % confidence.)

The thermal-neutron dose is evaluated from radium-gamma-ray calibrations with the aid of an empirical relation for the ratio between the gamma-ray and thermal-neutron doses producing the same density behind a cadmium shield of a thickness of about 1.0 mm.

Exposure record. The records are programmed for electronic data-processing, allowing analysis of personnel exposure by job-function and age, as well as by type of radiation. Annual as well as cumulative exposure records are kept.

Monitoring period. Four weeks.

Monitoring range (for routine automatic operation):

X- OR GAMMA-RADIATION	
0.016 MeV	From 0.005 to 0.160 r
0.059 MeV	From 0.005 to 0.080 r
From about 0.2 MeV up	From 0.015 to 1.0 r
BETA-RAYS	From 0.015 to 1.0 rem
THERMAL NEUTRONS	From about 0.020 to 0.60 rem
FAST NEUTRONS	From about 0.050 to more than 2 rem (if fog from X- or gamma-rays is negligible)

The range of the X- and gamma-ray readings above 0.2 MeV and of the beta-ray readings may be extended in emergency cases up to 2000 rem through quantitative X-ray fluorescence analysis [66].

5.5.2 Second example

Film holder for X- and gamma-ray monitoring. Commercially available plastic holder; open window, number aperture, three copper filters of thicknesses 0.05, 0.5 and 1.2 mm; 0.5-mm lead strip between two of the copper filters. All but the number aperture and the lead strips are symmetrical in front and back; the lead strips are somewhat offset (see Fig. 18).

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Film holder for X-, gamma-ray and neutron monitoring. Same holder as for X- and gamma-rays only, but three more filters are present: 0.6 mm Sn, 1.2 mm Sn and 1.0 mm Cd. Also, the badge has a filterless portion which holds the nuclear-track film.

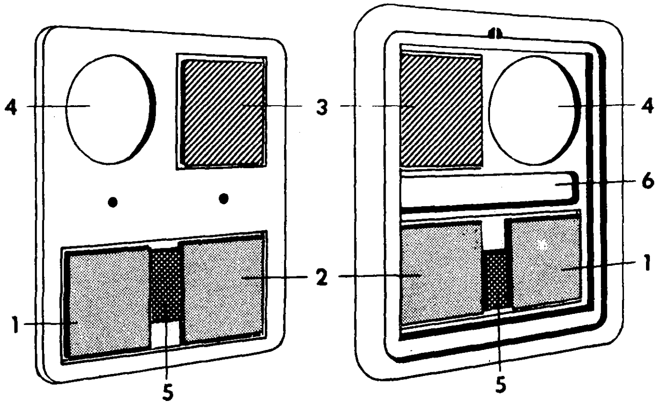

Fig. 18

Example 5.5.2; film badge

1 — 0.5 mm copper; 2 — 0.05 mm copper; 3 — 1.2 mm copper; 4 — Open window; 5 — 0.5 mm lead; 6 — Aperture through which number of the film packet is visible.

Films. Kodak Personal Monitoring Film, type 2; Kodak Personal Neutron Monitoring Film, type B.

Film-badge assembly. The back of the badge is held in position by a set screw; the number of the film packets shows through the numbering slit.

Badge identification. A commercially available percussion-press marks the outside of the packets as well as the films. A carbon ribbon is used for better legibility on the outside. Pressure is exerted from front and back.

Calibration:

(*a*) With X- and gamma-radiations, response is determined as a function of photon energy by means of heavily filtered bremsstrahlung and gamma-radiation from Au^{198}, radium (filtered with 1 cm lead) and Co^{60}-gamma rays, in perpendicular incidence. A

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full characteristic curve is obtained with X-radiation generated at about 80-kV exciting potential, with a total filtration of about 1 mm copper in the X-ray beam.

(*b*) In the case of beta-radiation, an attempt is made to calibrate with the particular radiation used by the station that is to be monitored.

(*c*) The fast-neutron calibration is carried out with a Po-Be source (2 c polonium). It is now planned to obtain a Pu-Be source (3 c plutonium).

Processing. The films are connected to each other with tape in a commercially available machine (Fig. 19), rolled on a developing reel and processed in X-ray developer like cinematographic film. A special nuclear-track developer [72] is used for the neutron films.

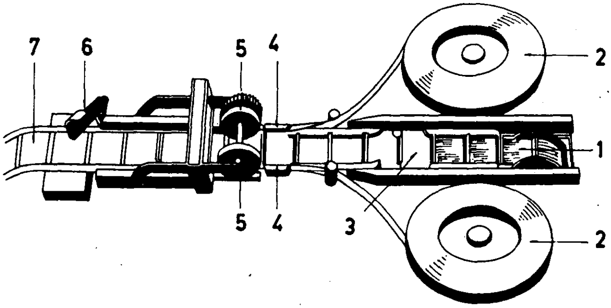

Fig. 19

Example 5.5.2

Connecting individual dental films for processing on reel

Evaluation. Essentially, X- and gamma-ray exposure is evaluated from the ratios of the exposures corresponding to the densities obtained in the open-window area and under the three copper or the two tin filters (or both), as a function of filter thickness. The exposure is first determined from the measured densities by use of the characteristic calibration curve obtained at 100 kV exciting potential. It is then corrected for the energy-dependence of the film response (Fig. 20) with the aid of a plot of the correction factors as a function of the ratios of exposures required for unit density under adjacent filter areas, as determined from the calibration curve. A representative plot of correction factors is shown in Fig. 21. For filters of the same material, these ratios are unique functions of the photon energy. Therefore, when the X- and gamma-ray film holder is

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used, the ratios are determined from the densities under the different copper filters only; when the film holder designed to monitor neutrons as well as X- and gamma-rays is employed, and

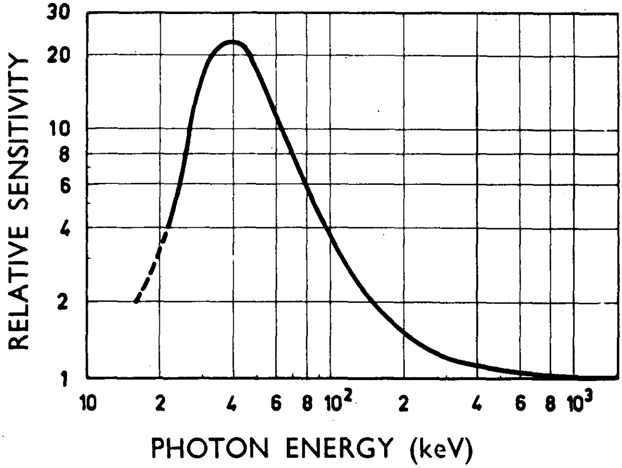

Fig. 20*

Example 5.5.2

Typical energy-dependence of a radiation-monitoring film

an evaluation is to be made of exposures obtained with very high energies of X- and gamma-radiation, the ratios are determined from the densities under the tin filters only.

In the absence of thermal neutrons, the areas under the same masses of tin and cadmium show roughly the same density. The presence of thermal neutrons is indicated by additional blackening under the cadmium. The calibration with a known thermal-neutron flux makes a quantitative evaluation of the thermal-neutron dose possible. The differentiation between soft X- or gamma-rays and beta-radiation is accomplished through the asymmetrical lead foil; in the presence of large amounts of incident beta-rays or electrons causing massive back-scatter from lead, the film area adjacent to the backing lead-foil is, as a rule, darker than the area that is covered with lead in front, or any of the other adjacent areas.

The method of determining the fast-neutron dose is similar to that described in the preceding example.

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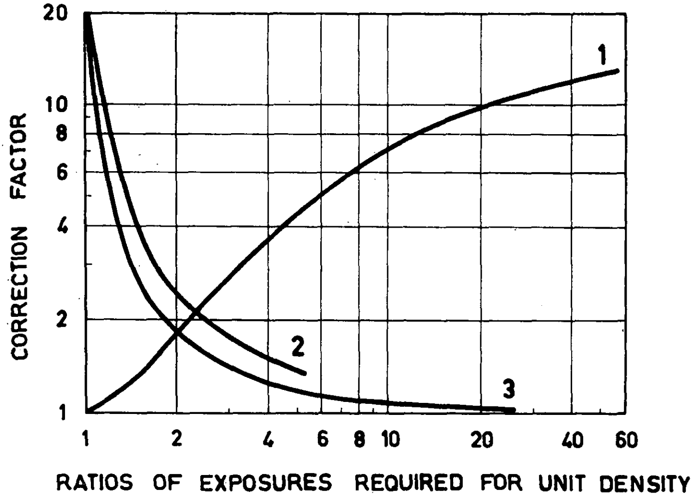

Fig. 21*

Example 5.5.2

Correcting for energy-dependence

1 — Ratio exposure for unit density at open window to exposure for unit density under 0.05 mm Cu; 2 — Ratio exposure for unit density under 0.05 mm Cu; 3 — Ratio exposure for unit density under 0.5 mm Cu to exposure for unit density under 1.2 mm Cu.

Exposure record. The record is kept on a card-index system, which makes the evaluation possible from a number of different points of view. Monthly and annual exposure doses for different groups of radiation workers are obtained with relatively little effort.

Monitoring period. One month, as a rule; for fast neutrons two weeks, if desired.

Exposure range monitored:

LOW-ENERGY X- AND GAMMA-RAYS (about 40 keV)	0.002 to 150 r
HIGH-ENERGY X- AND GAMMA-RAYS ..	0.040 to 1000 r
THERMAL NEUTRONS	0.020 to 400 rem (provided the X- and gamma-ray dose was less)
FAST NEUTRONS	0.020[a] to approx. 5.0 rem

[a] Applicable if the fog due to X- or gamma-ray exposure was negligible. The value of 0.02 rem is one-fifth of the maximum permissible weekly dose, based on a 40-hour week.

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5.5.3 Third example

This is an example for a station not using photographic film but photographic paper emulsions for personnel monitoring. Some of the noteworthy features of the service are:

Film holder. A plastic envelope with "button holes" containing a metal sleeve, that is to be slipped over one half of a dental-size film packet. According to the type of radiation monitored, the sleeve contains different filters. For the monitoring of hard gamma-rays and neutrons, the sleeve contains: a cadmium filter, 0.35 mm in thickness and a tin filter, 0.40 mm thick (see Fig. 22). For the monitoring of soft X-rays these filters are replaced by two copper filters, of thicknesses 0.2 and 0.6 mm, and for the approximate discrimination between beta- and gamma-rays by a filter of 1 mm aluminium.

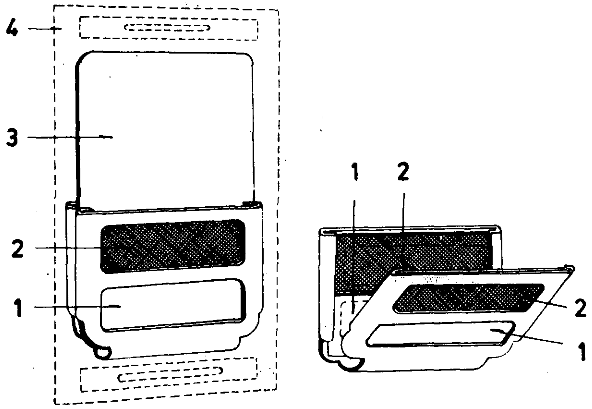

Fig. 22

Example 5.5.3; film badge

1 — 0.35 mm cadmium; 2 — 0.40 mm tin; 3 — Packet containing photographic papers; 4 — Plastic envelope.

Photo-sensitive material. Three strips of emulsions of differing sensitivity, placed side by side on a paper base, which in turn is mounted on a support of dental-film size, enclosed in a regular dental packet. Manufacturer: Kodak-Pathé. Kodak Personal Neutron Monitoring Film, type B, is employed for the monitoring of fast neutrons.

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Badge assembly. In addition to the three emulsion strips, the sensitive element carries a development-control strip which makes emergency development under non-standard processing conditions feasible. The packet with the filter sleeve is inserted into the plastic envelope, which is then sealed.

Badge identification. Through pressure marking of the packet outside and inside, the inside on a special paper marking strip.

Processing. In the commercial developer recommended by Kodak-Pathé for use with the particular photo-sensitive material.

Evaluation. Usually by visual comparison of the densities on the monitoring strips with those on the calibration strips. The proton recoil tracks are counted under a microscope (magnification factor 800, oil immersion, direct vision) by scanning a total length of 4 cm of emulsion.

Calibration. Characteristic curves are established for various qualities of X- and gamma-radiation, including radium-gamma rays (filtered through 20 mm lead) and X-radiation having the following characteristics:

Constant exciting potential (kV)	*Added filtration* (mm)	*Half-value layer* (mm)
60	0.5 Al	0.03 Cu
100	1 Al	0.16 Cu
150	2 Al	0.4 Cu
180	2 Al	0.4 Cu

The inherent filtration of the X-ray tube is 2 mm Al.

The thermal-neutron dose is evaluated from calibration checks obtained by exposure of film badges in a reactor thermal column. The neutron flux is determined by use of boron- and lithium-loaded nuclear plates. A calibrated neutron flux from a radium-beryllium source is used for the fast-neutron calibration of the nuclear-track films.

Monitoring period. Usually two weeks.

Exposure range monitored:

X-RAYS ($\leq$ 180 kV)	From 0.010 r to between 25 and 40 r
GAMMA-RAYS (radium)	From 0.010 r to 800 r

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THERMAL NEUTRONS	From 0.010 rem (or $^1/_{10}$ of gamma-ray dose) to 400 rem
FAST NEUTRONS	From 0.040 rem to 100 rem
BETA-RAYS (Sr^{90}/Y^{90}, filtered by 30 mg/cm^2)	From 0.020 rad to 800 rad

5.5.4 Fourth example

This is an example of a station having a comprehensive film-badge service, but nevertheless supplementing it with a complete set of additional detectors, mainly for use in accidents.

Film holder. Fig. 23 shows the details of the holder construction. Plastic, aluminium and lead, and cadmium interleaved with gold, are used as filter materials. Further elements included, mainly for the reliable analysis of neutron doses greater than 10 rad, are a sulphur pellet, another gold foil, and an indium foil. A chemical dosimeter and a silver-activated phosphate glass are also incorporated. Nevertheless, the over-all dimensions of the holder are only approximately 6.3 × 4.4 × 0.81 mm and it weighs about 33 grams. Note that there is a layer of plastic between the film packets and the front filters of the badge. Also, the identification insert (about 0.51 mm of plastic and paper) is over the "open window". In addition to this personnel dosimeter, a set of stationary threshold detectors is used.

The rest of the film-dosimetry procedure is quite similar to what was described in other examples.

5.5.5 Fifth example

This is another example of a station that has a complete film-badge service supplemented with a complete set of additional detectors for use in accidents.[*]

Film holder for beta-, X- and gamma-rays, and for thermal neutrons. (Fig. 24.) Hinged plastic case having an open window and the following absorbers: plastic, 300 mg/cm^2 and 150 mg/cm^2 respectively (approximately 3 and 1.5 mm thick); duraluminium 1.0 mm; lead, 0.3 mm, plus tin, 0.7 mm; lead, 0.3 mm, plus cadmium, 0.7 mm. The "slot" provided along one of the long sides of the holder for strapping the badge to the wrist or other parts of the body may also be used for attaching a "criticality pack" for use in the event of a reactor accident.

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[*] In the planning stage at the time this Manual was written.

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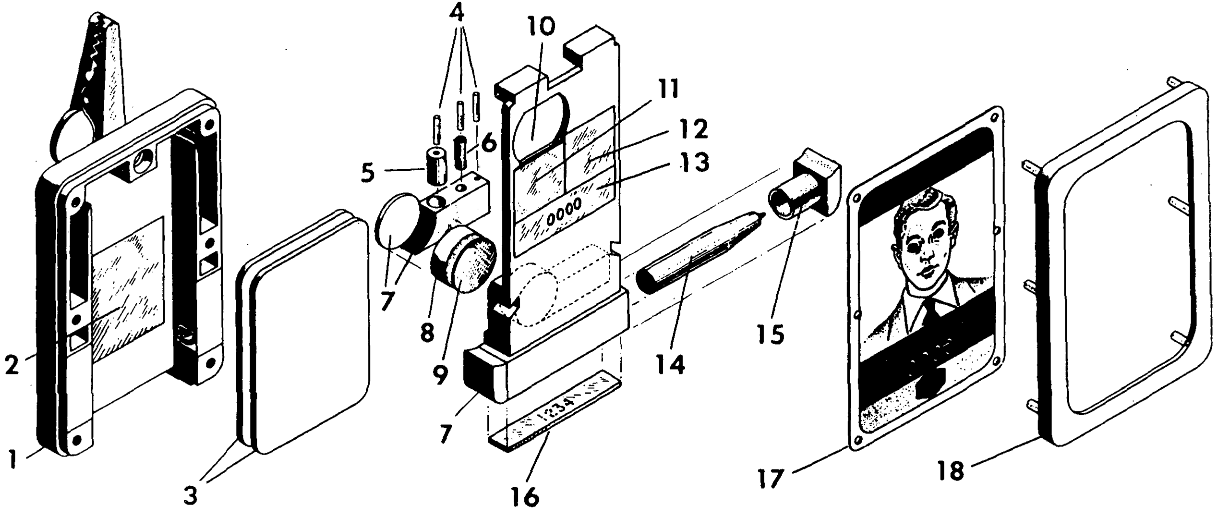

Fig. 23

Example 5.5.4; film badge

1 — Main body of badge, plastic; 2 — 0.25 mm lead; 3 — Film packets; 4 — Phosphate glasses; 5 — Copper sleeve; 6 — Lead sleeve; 7 — Plastic; 8 — Sulphur; 9 — Gold; 10 — Open window; 11 — Combination: 0.38 mm cadmium — 0.13 mm gold — 0.38 mm cadmium; 12 — 1.0 mm aluminium; 13 — Identification insert (0.25 mm indium); 14 — Chemical dosimeter; 15 — Plug; 16 — Badge number; 17 — Laminated identification insert; 18 — Front frame of badge.

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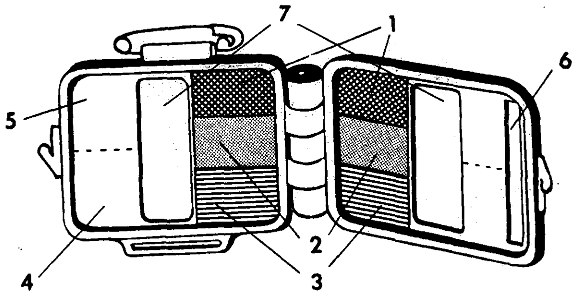

Fig. 24

Example 5.5.5; film badge

1 — 0.7 mm tin backed by 0.3 mm lead; 2 — 0.7 mm cadmium backed by 0.3 mm lead; 3 — 1.0 mm duraluminium; 4 — 3.0 mm plastic; 5 — 1.5 mm plastic; 6 — Recess for indium foil; 7 — Open window.

Also, a recess is provided for an indium foil, 0.5 mm thick, again for criticality purposes.

Holder for fast-neutron plates. Flat disc-type holders, made of aluminium, about 30 mm in diameter (Fig. 25).

Films. Kodak Radiation Monitoring Film is used for monitoring beta-, X- and gamma-rays and for thermal neutrons. Ilford K 2 nuclear-track plates (emulsion thickness 50 μm) cut to 25-mm squares are used for fast-neutron monitoring.

Badge assembly. Noteworthy feature of the fast-neutron badge assembly: two plates are placed with their emulsions facing each other but separated by 0.25 mm polyethylene.

Badge identification. Pressure marking of film packets and films inside.

Calibration. The energy-dependence of the badge response is determined with narrow bremsstrahlung spectral bands in the customary way, except that the badges are exposed at an angle of 45 degrees to the incident radiation which is thought to simulate conditions under actual use more realistically than exposure under perpendicular incidence. (Under these conditions of exposure the variation of the film sensitivity under the lead-plus-tin or lead-plus-cadmium filters as a function of photon energy is no more than 10% for "effective" radiation energies above 90 keV.) Furthermore,

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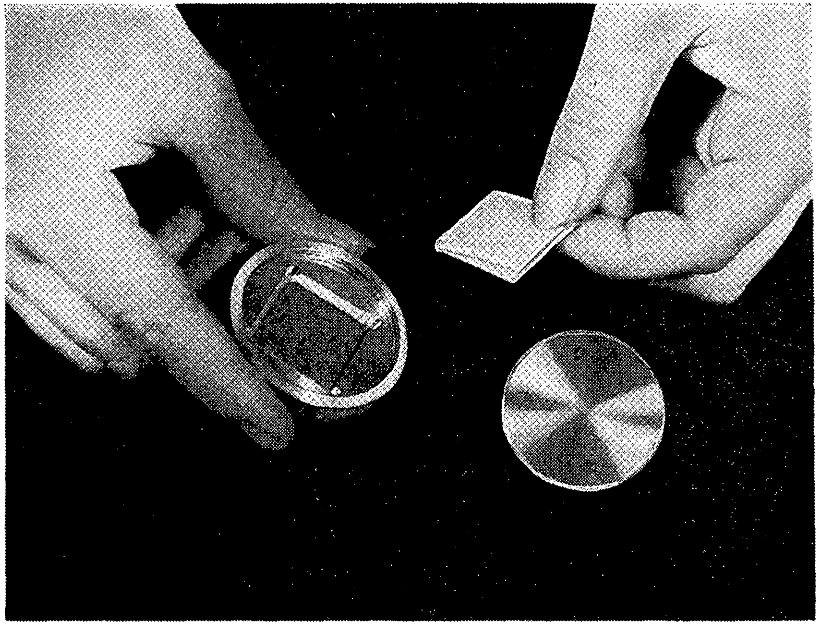

Fig. 25*

Example 5.5.5

Holder for nuclear-track plates

a density-*vs.*-exposure curve is prepared using radium gamma-radiation, again for the film regions filtered by lead-plus-tin (or lead-plus-cadmium).

The calibration for thermal neutrons is based upon response characteristics originally established in a calibrated reactor thermal column. A calibrated neutron flux from a radium-beryllium source is used for the fast-neutron calibration of the nuclear-track plates.

Processing. For the development of the monitoring films, commercially available developing frames, each accommodating 144 films, are used. (See Fig. 11, p. 54.) The developer is replenished according to the manufacturer's instructions. Both developer and fixer are discarded after the processing of 10 000 films. The nuclear-track plates are processed in a special developer [26].

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* From ref. [26].

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Evaluation. The conventional procedure of comparing ratios of densities in the various areas of the monitoring films with those obtained from calibration films is used for the evaluation of the beta-, X- and gamma-ray exposures. The plastic filters aid in the discrimination of beta-rays and soft X-rays; the duraluminium filter is used in the X-ray region up to around 90 keV; higher-energy X- or gamma-ray exposures may be determined directly from the densities under the lead-plus-tin (or lead-plus-cadmium) filter, without any correction to be applied to the radium calibration curve.

The proton recoil tracks in the nuclear-track emulsion are counted under the microscope with a magnification of roughly 1000, either by direct vision or by projecting the image on a screen. Each plate is scanned over an area of 0.014 cm^2, and the dose is determined by a comparison with the number of tracks counted over a similar area of the calibration plate.

Exposure record. A statistics and reporting section maintains address and movement cards for each individual monitored, as well as a complete, coded, punched-card record system allowing for a fast and easy analysis of cumulative exposure data.

Monitoring period. Two weeks.

Exposure range monitored:

X- AND GAMMA-RAYS around 0.040 MeV	0.001 to 100 r
X- AND GAMMA-RAYS around 1 MeV	0.020 to 2000 r
THERMAL NEUTRONS	0.010 to 1000 rem (RBE = 3)
FAST NEUTRONS	lower limit 0.050 rem, upper limit depending on degree of X- or gamma-ray fogging (under severe conditions as low as 3—5 rem)

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