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Australian Radiation Laboratory

Personal Monitoring and Assessment of Doses received by Radiation Workers

by

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ABSTRACT

This report gives an outline of the Personal Radiation Monitoring Service operated by the Australian Radiation Laboratory. This Service utilizes different types of monitors for assessment of doses received by radiation workers and these monitors are described.

The doses reported in the Service have been collated and the distribution of doses received by radiation workers in the different occupational categories determined. From these distributions, the average doses received by radiation workers have been assessed and the maximum likely additional increase in cancer deaths in Australia as a result of occupational exposure estimated. This increase is shown to be very small compared with the existing mortality rate. There is, however, a considerable spread of doses received by individuals within occupational groups and there could therefore be room for further reduction of radiation exposure in a number of instances.

INTRODUCTION

In order to ensure that prescribed limits of exposure to radiation for radiation workers are not exceeded, some form of radiation monitoring is necessary. When exposure is to external radiation sources only, monitoring is often carried out by wearing personal monitors on the body. Such monitors measure the amount of photon radiation (i.e. Xrays and γrays) and corpuscular radiation (i.e. βrays and neutrons) received at the position of wearing.

From the measurements made on monitors, it is possible to assess the doses received by the whole body or by specific organs of the body, provided information is also available on the energy of the radiation to which the monitor and the radiation worker have been exposed, on the uniformity and extent of the radiation field and on the depth of the organs of interest in the body although in practice these would be based on "reference man" (ICRP 1975) for calculation purposes. However, from the everyday point of view, it is not convenient to determine the dose to the whole body or to specific organs from the monitor results. In practice, if the annual dose for an individual, as determined from the monitor results, does not exceed 50 mSv then the dose-equivalent limits for the whole body and for the various organs will not be exceeded provided the monitor has been worn on the body in a position such that its response corresponds to the highest dose received by the body. Unless it becomes necessary to determine the dose equivalents for specific organs, it is usual to measure the radiation received by the body by wearing the monitor at either chest or waist level.

THE ARL PERSONAL RADIATION MONITORING SERVICE

The Laboratory has operated a Personal Radiation Monitoring Service since the early 1930's so that persons who are occupationally exposed to radiation can determine their resulting dose equivalents.

Two types of monitor are available for assessment of whole body exposures. One is a film badge which consists of a combination of a personal monitoring film placed inside a plastic holder containing various materials to modify the radiation incident upon the film. The other is a thermoluminescent dosemeter - known as a TLD badge, which consists of TLD discs mounted inside another type of plastic holder.

In addition to the above monitors, two special monitors are available. One of these is a neutron film for use in determining the doses received from neutron sources and the other is a finger sachet for assessment of doses received by fingers when these doses are likely to be significant.

Technical aspects of badges used for assessing dose equivalents are described hereunder:

(a) Personal monitoring films

In the Service operated by the Laboratory, personal monitoring films are issued to establishments for wearing by radiation workers for periods up to 4 weeks. The wearing period depends on the type of radiation work carried out and on the expected exposure levels. The films are always accompanied by control films from the same batch of films to provide a base density level for the worn films, to detect any extraneous radiation exposure of the films and to detect any abnormal environmental conditions that may affect the films. Control films are always developed with the worn films upon their return to the Laboratory. In addition, films, referred to as standard films are exposed in the Laboratory to known radiation doses from specified sources and these are also developed with films returned from establishments. They are used to assess the doses received by the films worn by radiation workers.

The films used have a slow emulsion on one side of the film base and a fast emulsion on the other. Silver halide grains in the emulsions absorb energy when exposed to radiation and form a "latent image" which becomes observable as a photographic density when the film is developed. The resultant density depends on the radiation dose and on the energy of radiation to which the film has been exposed. For a given radiation energy, the density of the developed film is not directly proportional to the exposure and allowance for non-linearity in this relationship must be made in assessing a dose. The response curve obtained depends on the actual conditions used in developing the films and the use of the standard films referred to above allows the determination of this relationship for each batch of films developed. A typical curve is illustrated in Fig 1. The second factor relates to the response of the film with different radiation energies when the same dose is delivered to the film. The response with energy depends on the different absorption and scattering processes occurring in the silver halide grains. A typical curve for different energy photons is shown in Fig 2. This response may vary slightly with films in different manufacturing batches. The relative change for each batch of different emulsion number is determined when films are received from the supplier by exposing a number of films from each batch to defined doses using standard radiation beams and by determining the corresponding responses of the films. Changes in reponse are taken into account in assessing the doses on films returned from establishments.

Films can be used for measurement of doses over the approximate range from 10 μSv to 3,000 μSv for Xrays and 60 μSv to 50,000 μSv for γrays. If larger doses are received, the fast emulsion on the film can be removed from the film base and doses up to 0.1 sievert (Sv) for Xrays and 2.5 Sv for γrays can then be measured using the slow emulsion only. In practice, the doses on more than 99^{0}/o of films can be determined without removal of the fast emulsion.

It is also possible to use films to assess β-ray dose, but there are some restrictions to the β-ray energy for this purpose. These result from the thickness of the paper wrapping around the film and the thickness of the protective coating above the first emulsion of the film. Even the emulsion has an absorptive effect and some of the βrays may not penetrate far enough to render the silver halide grains developable. In order to assess the dose from βrays they must have a minimum energy of about 70 keV so as to reach the emulsion.

The assessment of the dose received by a film is complicated by the need to take a number of factors into account. In order to facilitate the assessment, knowledge of the radiation energy to which the films have been exposed is important. Whilst this information is not difficult to obtain in a number of cases, it does create problems when persons wearing monitors have been exposed to mixtures of different types of radiation, e.g. βrays and Xrays, and to radiations of different energies. For this reason, films are worn in special plastic holders which contain filters of different materials to attenuate the radiation beams to differing extents. The holder used in the Service is of a type designed for use in radiation protection services in the UK (Heard 1965) and is also used in some other countries. It is illustrated in Fig 3.

The response of film to radiations of different type and energy depends considerably on the section of the film badge holder through which the radiation passes. For photons, the response curve shown in Fig. 2 is not significantly changed when photons pass through areas 1, 2 and 3 of the holder, but is lowered when photons of energy below 0.1 MeV pass through area 4 (corresponding to the dural filter). For areas 5 and 6 (corresponding to the cadmium-lead and tin-lead filters), photon energies below about 0.1 MeV result in no significant increase to the film base density, unless the dose received is very large. Between 0.1 and 0.3 MeV, the response for a given dose increases slowly and then becomes reasonably steady above this energy. For assessment of βrays, areas 2 and 3 of the holder provide different thicknesses of plastic absorber to assist in assessment of β-ray energy and the dose from βrays.

Inspection of the developed films usually gives a good indication of the radiation energy to which a film has been exposed and this can be confirmed by measuring the densities of the film in several areas and comparing the relationships of these densities with each other. As a general rule, assessments can be made by measuring areas 1, 2 and 3 for β-ray exposures, areas 1, 4 and 5 for diagnostic X-ray exposures, areas 1, 2, 3, 4 and 5 for a mixture of β-ray and X-ray exposures and areas 5 or 6 for γ-ray exposures. The appearances of films exposed to βrays, to diagnostic Xrays, to a mixture of βrays and superficial therapy Xrays and to γrays are shown in Fig. 4.

The normal personal monitoring films cannot be used for assessment of neutron dose, except for doses from thermal neutrons. These neutrons are absorbed by the cadmium-lead filter in the film-badge holder and γrays are emitted from this filter and affect the film immediately adjacent to it. Thus, the increased blackening caused by these γrays in area 5 can be compared with any blackening under the tin-lead filter (area 6), as this filter will attenuate γrays to the same extent as the cadmium-lead filter. The dose due to thermal neutrons is derived from this increased blackening.

Small errors will always arise in the assessment of the doses received by films due to variations in the response of film to the same radiation from one batch of film to another, in the fog levels of the individual films in a batch, in the processing of films and in the measurement of densities of the various areas of the films. These variations are all small, controlled and allowed for in assessments. Larger errors may derive from the assessment of the effective radiation energy to which films have been exposed, particularly if the films have been exposed to a wide range of radiation energies within an establishment. This effective energy can be determined from the energy stated by the user when returning films for development and from the appearance of the films after development. The larger errors are dependent on the assessed effective energy and on the area measured on a film.

Taking into account the errors referred to in the preceding paragraph, the maximum errors likely to arise in assessing doses on films are given in Table I for the various radiation energies to which films are exposed. However, in many cases, the errors are substantially smaller. Further errors can also arise from accidental or unwitting exposure to radiation or if environmental conditions are not suitable. Such errors are not allowed for in Table I.

(b) TLD badges

During the past two years, a TLD badge has been developed in the Laboratory for personal monitoring purposes. This badge utilizes $CaSO_4$:Dy in two teflon discs mounted in a plastic container (Boas 1981). The energy response of the discs is of a similar form to that of film, but the response of one of them has been modified by mounting copper filters on each side of it in the holder. This makes it possible to obtain an assessment of the energy of the radiation incident on the badge.

This badge was designed primarily for use in the uranium mining industry, where it is used under conditions of high temperature and humidity without adverse effects. Accordingly, it can be worn for much longer periods of time than can the personal monitoring films. It is also used occasionally for measurement of doses in other radiation fields where the use of film is contra-indicated. Upon return of the badges to the Laboratory from establishments, the TLD discs are readout and the doses received are assessed, taking into account the energy of the radiation involved. After readout, the discs are annealed and their characteristics re-assessed when necessary before re-issue.

(c) Neutron monitoring films

Radiation workers may be exposed to neutrons when using certain radioactive sources - e.g. radium/beryllium, americium-241/beryllium, californium-252, or when using certain particle accelerators. The normal personal monitoring films cannot be used for the measurement of the doses from neutrons. For this purpose, a special film with an emulsion which allows neutron-proton interactions to take place is used. The resultant protons produce tracks in the emulsion and these are observed through a microscope after development of the film.

In order to determine the dose received by a film, standard neutron films are exposed to known neutron doses from an americium-241/beryllium source and the tracks produced on the films are then counted in order to obtain a correlation between the number of tracks produced and the neutron dose. Because the collision stopping power of neutrons in water (referred to as the quality factor) and the biological effects produced by neutrons in tissue are much higher than for Xrays or γrays, each track produced in the film emulsion represents a relatively large dose.

Most radioactive sources which emit neutrons have a broad energy spectrum, with peaks at about 4-5 MeV. The spectrum of the americium-241/beryllium source used for standardizing purposes can be considered to be representative of the spectra from these other sources. However, in the working situation, the energies of neutrons may differ by the time they reach the film. Although the sensitivity of film to the different neutron energies may not vary greatly, there could be variations in the quality factors to be used for the assessment of dose. In practice a mean quality factor of 10 is used for all neutrons in determining the dose equivalent from the counted number of tracks.

The neutron doses received are assessed by counting the tracks produced in the emulsion, using a microscope with magnification of 1500. To detect each track, the microscope is adjusted for each viewing field so that the full depth of the emulsion is scanned. As it is not possible to scan the whole film, fields are selected on a random basis, but this can lead to errors in estimating the average number of tracks per field in the film from the neutron-proton interactions. Counting is routinely made in 100 fields for each film, each field being of diameter 0.04 mm, but 200 fields are scanned when necessary. Quite often only one or two tracks may be observed on a film.

From time to time tracks may be produced by cosmic radiation and if this occurs and is not ascribed to cosmic radiation, an overestimate of the dose resulting from the radiation source will occur. Difficulties in accurate assessments of dose also occur as the tracks produced in the emulsion fade relatively quickly, particularly under conditions of high humidity, as illustrated in Fig. 5. Prompt development of films after each wearing period is carried out in order to minimize the fading of tracks. Because of the inherent difficulties in assessing doses from neutron sources, large errors may arise which cannot always be allowed for. Hence the doses reported for these films are only regarded as a guide to the doses actually received.

(d) Finger sachets

Finger sachets consist of thermoluminescent material (lithium fluoride, LiF:Mg, Ti) in powder form within a plastic container that is formed into a ring and worn on the finger. They are often used by persons handling high activity radioactive sources, such as those used in the treatment of patients, or by persons using X-ray diffraction units, etc. The LiF powder used in them is relatively energy independent - the sensitivity only increasing by about $30^{0}/o$ at 20 KeV above that for higher energy photons. This simplifies the assessment of dose. However, the minimum dose that can be read is about 100 μSv (10 mrem). As with the discs in the TLD badges, the powder is annealed after readout and its characteristics re-assessed before re-use.

OCCUPATIONAL EXPOSURE LEVELS

All persons using the Personal Radiation Monitoring Service are classified into the various categories given in Table II. In addition, the various establishments using the Service are classified into different groups according to the type of work and (radiation) work-load carried out in them. Thus, establishments which carry out the same type of work may be classified differently as there could be significant differences in the doses received by workers in them. These establishment categories are given in Table III.

Periodically, data are collated from the Service on the doses received by radiation workers in the various occupational groupings and, where considered appropriate, also in the different types of establishment. Data for the year 1978 are reported in Table IV. This Table gives the frequency of doses reported in dose ranges for various occupational groups. The data are further illustrated in Fig. 6 for selected occupational groups. These figures show quite clearly the wide ranges of doses received in medical diagnostic radiology, in the nursing of patients who have radioactive sources in situ and in carrying out industrial radiography in non- or partially-shielded areas. They also show that in dentistry and in research and industrial applications using totally shielded radiation sources, the ranges of doses received by workers are very small and the doses low.

The data in Table IV have also been collated to give the mean annual doses received by various occupational groups and these are given in Table V. The Table shows that the annual effective dose equivalents are well below the limit of 50 mSv. In deriving these figures, it has been assumed that employment is over a 48 week year. In a number of cases, persons in an establishment may have discontinued use of the Service, but others may have taken their place. Accordingly, in the Table, the number of persons monitored refers to the effective number of persons in the establishment monitored for the year. In other cases, establishments may have commenced use of the Service or discontinued the Service through the year. If this has been due to a change in radiation use, then this was taken into account in deriving the figures quoted. On the other hand, if the establishment continued to use radiation sources outside the monitoring period, then it was assumed that radiation was received at the same rate as during the monitoring period.

The prescribed annual limits of exposure for radiation workers refer to the annual dose-equivalent limit for uniform whole-body exposure. As such exposure rarely occurs in practice, recourse must be made to evaluation of the effective dose equivalent. This requires calculation of the dose equivalent to several organs from the reported monitor doses and the application of appropriate weighting factors to these organ doses. Calculation of effective dose equivalents for individual radiation workers is impossible, due to the variations in their physique. Calculations are therefore based on "reference man" and on typical exposure conditions for each occupational category.

From a practical point of view, the calculation of effective dose equivalent assumes that radiation workers are exposed in reasonably uniform radiation fields. If this is not the case, the dose recorded by a monitor is assumed to correspond to the highest dose received by any one of the appropriate organs. Accordingly the dose equivalent, as calculated, would be a maximum value. The organs used for calculation of the effective dose equivalent are those recommended by the National Health and Medical Reseach Council (NHMRC 1981), where the 'remainder' as given in those recommendations has been taken to include the gastro-intestinal tract and liver, which in all probability would be the organs in the body receiving the highest doses, other than those specifically listed. The depths of the organs in the body were derived from Eycleshymer (1970) for "reference man" and the factors for absorption in tissue of the different energy Xrays and γrays for these depths were derived from published depth dose data (Cohen 1972). These factors were multiplied by the NHMRC recommended weighting factors for the various organs in order to obtain the multiplying factors given in Table VI.

The average annual effective dose equivalents have been calculated by application to the average doses for the various occupational groups of the appropriate multiplying factors and are included as part of Table V. These values should be compared with the annual limit of 50 mSv. The values show that the average dose equivalent for radiation workers as a whole is 0.5 mSv, i.e. only $1^{0}/o$ of the annual limit.

From the above estimate of the average dose equivalents received by radiation workers, the increased risks of fatal radiation-induced cancers arising in the population from the exposure of radiation workers can be estimated. Watson (1977) gives a figure for whole-body exposure of one per hundred man-sievert for all radiation-induced cancers (including leukemia). This figure is an average for a population comprising persons of all ages and sex. The risk for any individual group of persons and any particular type of cancer is dependent on the age and sex of individuals in that group and the sensitivity of the irradiated organs and tissues. Estimates of risk for an individual are therefore extremely difficult to make, but if Watson's figure is used, ignoring other variables, it corresponds to a risk of induction of cancer in a radiation worker receiving the average dose equivalent of 0.5 mSv in one year of 5 in one million. The increase in cancers in Australia arising from the total exposure from radiation work can be calculated on the basis of the above risk estimate and on the assumptions that the ARL Service covers approximately one half of radiation workers in Australia and the dose distribution amongst the other workers is similar to that for workers using the ARL Service. The total annual dose contribution to radiation workers is derived by doubling the sum of the products of the total number of workers and the average annual effective dose equivalents for each occupational classification given in Table V. This leads to a value of 6.2 man-sievert, which on the basis of Watson's risk estimates, corresponds to an incidence rate of about 1/16 case per year, i.e. one case in every 16 years. This is to be compared with the mortality rate of some 20,000 cancer deaths per year in Australia (ABS 1979). The estimate of 1 case every 16 years represents a maximum number of cases on the basis of a linear relationship between radiation dose and effect and on the exclusion of any threshold doses, if such doses do exist.

The genetically significant dose (GSD) to the Australian population has also been evaluated from the data collated from the ARL Service. This is defined as that dose which if received by every member of the population, would be expected to produce the same genetic injury to the population as do the actual doses received by the various individuals. It can be expressed by the formula

$$GSD = \frac{\Sigma D_{go} P_i N_{io}}{\Sigma \ P_i N_i}$$

where	D_{go}	is the average gonadal dose for radiation workers in occupational group o
	P_i	in the average child expectancy of persons in age group i
	N_{io}	is the number of radiation workers of age group i in occupational group o, and
	N_i	is the number of persons of age group i in the whole population.

As the above parameters differ according to sex, the final value of the genetically significant dose is determined by summation of the data for each sex.

The average gonadal doses for radiation workers in the various occupational groups are included in Table V. These have been derived from the doses reported on the monitors worn in the Service and from the gonadal dose multiplying factors included in Table VI. These factors allow for absorption of radiation in overlying tissue and are dependent on the radiation energies or radioactive materials to which radiation workers have been exposed.

Some years ago, the Laboratory sought information on the age distribution of radiation workers in the various occupational groups and although the information received was not complete, it was adequate to determine the relative numbers of persons likely to be in each sex and age group (UNSCEAR 1977). The distribution is given in Table VII, which enables evaluation of the values of N_{io} in the above formula. Data for P_i are taken from Swindon (1980) and although the data apply to 1970, any changes occurring since then would not have a significant effect on the final value of the GSD. Values of N_i have been estimated from census statistics (ABS 1979). Using the above formula, the annual genetically significant dose contribution to the population is 550 x 10^{-6} mSv. This is of the order of 0.06°/o of that arising from natural background radiation. The contribution for each occupational group to this dose is included in Table V.

An alternative approach to the calculation of the annual GSD has been given by Binks (1960) who has used a simplified method. This calculation assumed that the age distribution of male radiation workers is from 18 to 60 years of age and that the genetically effective fraction of these is one third, whilst for females, it is assumed that they are all in the lower age group and the genetically effective fraction is one. The annual GSD is therefore the product of the annual average gonadal dose, the number of workers and the genetically effective fraction for each group. The results show that the contribution is 700 x 10^{-6} mSv i.e. about 0.07°/o of the contribution from natural background radiation. This value is not very different from that obtained using the more rigorous method of calculation and this simplified method appears suitable when data relating to the age and child expectancy factors for a given population are not available.

The life-time doses received by radiation workers are of growing interest, as the risks of radiation-induced illnesses will increase with the cumulative doses received, or likely to be received. Whilst cumulative records can only give the occupational doses received by individual workers up to any point in time, it is important to assess the total likely doses that radiation workers would receive during their working life-time. Reference has been made to an earlier survey carried out by ARL on the age distribution of radiation workers in various occupational groups. In this survey, information was also sought on the number of years that workers had been exposed to radiation in the various groups and from this it has been possible to make some estimates of the likely number of years of occupational exposure for persons in these groups.

By combining the likely working-life times of persons in a group with the average dose received by persons in the group, the likely life-time doses of radiation workers can be evaluated. Table VIII gives the likely working-life times and the likely life-time effective dose equivalents for radiation workers. This Table shows that for most occupational groups, the likely life-time doses are considerably less than the limits prescribed for one year's exposure for radiation workers. It appears that the annual prescribed limits are only likely to be exceeded in a life-time by radiologists in clinics and private practices and in gynaecological treatments performed by radiotherapists and gynaecologists.

Attempts have been made to compare the values given in this Report with those reported for other countries. Such intercomparisons are difficult due to the different methods used for classifying occupations and establishment types. However, where comparisons are possible, the average annual dose equivalents reported here are not greatly different to those reported in other countries.

CONCLUSION

A study of the data presented in the various Tables in this Report and of the conclusions drawn from the data shows that there is considerable variation in the doses received by individuals in any one occupational group and between the average doses of the different occupational groups. It therefore seems that there could be room for improvement in techniques, procedures and facilities provided in a number of establishments using radiation sources and this would result in a further reduction of radiation exposure of persons. Nevertheless, the Report does show that overall, any increased incidence of fatal radiation-induced cancers in the population due to the doses received by radiation workers would be insignificant and the risk to the individual worker would be correspondingly small.

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REFERENCES

ABS (1979) Australian Bureau of Statistics. Year book Australia, no. 63.

Binks, W. and Marley, W.G. (1960) The hazards to man of nuclear and allied radiations: A second report to the Medical Research Council. Appendix G. London: H.M.S.O.

Boas, J.F., Murray, A., Young, J.G. and Johnston, P.N. (1981) Testing of $CaSo_4$:Dy in teflon discs as a thermoluminescent dosimetry material for personal monitoring of uranium mine and mill workers. Melbourne: Australian Radiation Laboratory; Report ARL/TR031.

Cohen, M., Jones, D.E.A. and Green, D. (ed) (1972) Central axis depth dose data for use in radiotherapy. Brit. J. Radiol., Supplement 11.

Eycleshymer, B.S. and Shoemaker, D.M. (1970) A cross-section anatomy. New York: Appleton - Century - Crofts.

Heard, M.J. (1965) Photographic radiation dosimetry and the development of the AERE/RPS film dosimeter. J. Phot. Sci. 13, 32.

ICRP (1969) Protection against ionizing radiation from external sources. A report of Committee 3 of the International Commission on Radiological Protection. Oxford: Pergamon Press; ICRP Publication No. 15.

ICRP (1975) Report of the Task Group on Reference Man: a report prepared by a Task Group of Committee 2 of the International Commission on Radiological Protection. Oxford: Pergamon Press; ICRP Publication No. 23.

National Health and Medical Research Council: Recommended radiation protection standards for individuals exposed to ionising radiation. Australian Government Publishing Service, Canberra.

Swindon, T.N., Morris, N.D. and Solomon, S.B. (1980) Contributions to the genetic and mean bone-marrow doses of the Australian population from radiological procedures. Melbourne: Australian Radiation Laboratory; Report ARL/TR017.

UNSCEAR (1977) Sources and effects of ionizing radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 1977 report to the General Assembly, with annexes. New York: United Nations.

Watson, G.M. (1977) Estimates of risk for radiation carcinogenesis and mutagenesis. Canberra: Australian Government Publishing Service; Australian Ionising Radiation Advisory Council Report No. 3.

TABLE I. Maximum errors in assessment of dose on a film

Radiation type	Maximum errors*	
	μSv	percentage
30 - 50 kVp Xrays	± 20	± 20
50 - 120 kVp Xrays	± 20	± 15
120 - 250 kVp Xrays (medium filtration)	± 20	± 20
200 - 300 kVp Xrays (heavy filtration)	± 50	± 10
γrays from single specified radioactive sources	± 100	± 10
γrays from single unspecified radioactive sources	± 100	± 30
βrays above 70 keV	± 100	± 50
mixtures of radiation sources (excluding βrays)	± 150	± 50

* The error applicable is the greater of the two values listed for any one radiation type.

TABLE II. Classification of occupations

- Radiology
  - Radiologists
  - Medical practitioners
  - Radiographers and others X-raying patients
  - Assistants to above
  - Receptionists, office workers, etc

- Radiotherapy
  - Radiotherapists, dermatologists, gynaecologists
  - Hospital physicists, therapy radiographers
  - Those nursing patients with radioactive sources in situ
  - Assistants to above
  - Receptionists, office workers, etc

- Nuclear medicine
  - Nuclear medicine technologists
  - Assistants to above
  - Receptionists, office workers, etc

- Dentistry
  - Dentists
  - Assistants to above
  - Receptionists, office workers, etc

- Chiropracty
  - Chiropractors, osteopaths, etc
  - Assistants to above
  - Receptionists, office workers, etc

- Veterinary
  - Veterinary surgeons
  - Assistants to above
  - Receptionists, office workers, etc

- Industry, Research and Education
  - Those using X-ray diffraction units and/or electron microscopes, etc
  - Those working outside totally enclosed installations
  - Those using non or partially enclosed radiation sources in industry or research (other than below)
  - Those using radioactive isotopes in tracer techniques in industry or research
  - X-ray and/or maintenance engineers
  - Teachers and/or demonstrators
  - Students (other than post-graduate research included in above classifications)

TABLE III. Classification of establishment type

Diagnostic radiology
- Small hospital department with one or two radiographers
- Large hospital department with more than two radiographers
- Private radiological practice
- Other medical practices

Radiotherapy
- Dermatology
- Radiotherapy department or practice (including gynaecology)

Nuclear medicine department or practice

Dental hospital or practice

Chiropractic practice

Veterinary practice

Industry

Research organization

Educational institute

NOTE: When an establishment is involved in more than one discipline, it may be classified into two or more of the above groupings according to the occupational description given.

TABLE IV. Number of monitors assessed in various dose equivalent intervals for specified monitoring periods (1978)

Occupational classification	Monitoring period (weeks)	Dose equivalent intervals (μSv)												
		0	10	20-40	50-90	100-240	250-490	500-740	750-990	1000-1990	2000-2990	3000-3990	4000-4990	>5000
<u>Radiology</u>														
Radiologists in hospitals	2	90	9	23	36	58	32	4	2	4	1			
	4	864	225	366	304	313	129	43	17	18	4	1		
Radiologists in clinics and private practices	2	6	1	3	4	16	34	8	3					
	4	139	23	67	85	123	79	14	13	11				
Medical practitioners in hospitals	1	62			1	13	3	1		1				
	2	18	2	7		7	4	1						
	4	472	45	40	17	38	24	7	4	8	3			
General practitioners	2	18	1											
	4	692	85	84	30	46	29	8	5	10	5			
Radiographers in hospitals and private practices	2	576	215	550	393	237	76	17	11	17	1			2
	4	3979	1705	4026	2702	1956	534	98	49	38	3	2	1	1
Assistants, nurses, porters, etc	1	171	2	1	9	27	21	12	3	2				
	2	142	56	114	40	38	11	1						
	4	3091	600	1092	583	368	89	17	6	8	3		1	
Maintenance engineers	4	175	15	11	5	1	5							

TABLE IV Cont.

Occupational classification	Monitoring period (weeks)	Dose equivalent intervals (μSv)												
		0	10	20-40	50-90	100-240	250-490	500-740	750-990	1000-1990	2000-2990	3000-3990	4000-4990	>5000
Dermatology, radiotherapy and gynaecology														
Dermatologists	2	25	6	10	2	2								
	4	226	34	35	9	18	6	7	4	7			1	
Radiotherapists and gynaecologists	1	28			3	14	17	12	3	1				
	2	13	1	5	4	6	3	2	2	1				
	4	154	7	8	1	10	11	2	1	2				
Therapy radiographers and hospital physicists	1	18			6	6	16	9	3	12				
	2	14	3	4	7	3	3	2		1				
	4	1298	106	108	76	177	126	43	12	23	6	1	2	3
Those nursing patients with sealed sources in situ	1	1433	6	1	114	454	439	201	84	72	2			1
	2	51	3	4	3	24	23	8	6	3			1	
	4	1198	63	66	29	166	165	91	62	94	19	10	3	
Nuclear medicine														
Nuclear medicine technologists and assistants	2	43	4	8	6					1				
	4	4415	250	308	163	209	154	32	16	10	1		2	
Dentistry														
Dentists	2	997	54	60	13	2	1	1						
	4	4084	283	390	80	42	8	2		2				
Dental nurses and assistants	2	153	5	7	1									
	4	3795	196	177	21	5	5	1		1	1			

TABLE IV Cont.

Occupational classification	Monitoring period (weeks)	Dose equivalent intervals (μSv)												
		0	10	20-40	50-90	100-240	250-490	500-740	750-990	1000-1990	2000-2990	3000-3990	4000-4990	>5000
Chiropracty														
Chiropractors	2	124	9	16	8	4	1							
	4	674	89	141	53	20	2		1					
Assistants	4	209	6	5	1	1								
Veterinary														
Veterinary surgeons	2	266	11	8	2		1			1				
	4	1518	85	116	46	34	14	2	1	4	2			
Assistants	4	1144	46	61	33	12	4			4	5	4	1	
Receptionists⊕	2	452	18	16	23	4		2		2				
	4	3455	193	200	61	56	29	7	5	5	2			

⊕ Covering all medical and allied groups

TABLE IV Cont.

Occupational classification	Monitoring period (weeks)	Dose equivalent intervals (μSv)												
		0	10	20-40	50-90	100-240	250-490	500-740	750-990	1000-1990	2000-2990	3000-3990	4000-4990	>5000
Industry and Research														
Users of X-ray analysis units, electron microscopes, etc	4	3839	51	44	11	11	4	2	1					1
Users of enclosed installations[+] or "quality control" sources, e.g. package monitors, thickness gauges, etc	2	277	7	4	1	6	7		2	1	1			
	4	4306	48	63	22	23	19	8	2	7	4			
Users of open installations[++], including industrial radiographers	1	894	41	126	78	147	139	77	38	44	13	2		2
		518	1	3		15	17	10	1	9	2		2	
	4	3393	80	60	29	49	46	26	12	14	1	1	2	
Users of radioactive tracers	2	90	1		1		4	3	1	1				
	4	3517	124	151	82	143	126	58	20	19	5	1		2
Installation and maintenance engineers	4	1048	30	63	39	25	16	7	2					
Education														
Teachers or demonstrators	2	158	2	2				2						
	4	1584	38	23	8	21	13	2	3			2		
Students	2	112	14	12	2	2								
	4	1890	321	367	96	73	14				2		2	

[+] An installation in which the radiation source and irradiated objects are within a total enclosure, access to which is prevented by physical means during irradiation (ICRP publication 15).

[++] An installation in which the radiation source and irradiated objects are within a defined enclosure, access to which is prohibited during irradiation (ICRP publication 15).

TABLE V. Average occupational doses to radiation workers in Australia (1978)

Occupational classification	Effective number of workers		Percentage of dose from photons of energy $>150\text{keV}_{eff}$	Average annual dose equivalent (monitor values) (mSv)	Average annual effective dose equivalent (mSv)	Average annual gonadal dose equivalent (mSv)		G.S.D. contribution ($\times 10^{-6}$ mSv)
	male	female				male	female	
Radiology								
Radiologists in hospitals	170	31		1.2	0.9	1.2	0.4	21
Radiologists in clinics and private practices	46	3		2.3	1.7	2.2	0.3	5
Medical practitioners in hospitals	50	8		1.0	0.6	0.9	0.7	6
General practitioners	74	12		0.2	0.2	0.1	0.0	1
Radiographers in hospitals and private practices	534	811		0.8	0.5	0.8	0.2	106
Assistants, nurses, porters, etc	102	408		0.5	0.4	0.5	0.3	22
Maintenance engineers	16	2		0.2	0.2	0.2	0.2	*
Dermatology, radiotherapy and gynaecology								
Dermatologists	19	12	5	1.0	0.3	0.3	0.1	*
Radiotherapists and gynaecologists	13	7	70	2.0	1.8	2.5	0.9	3
Therapy radiographers and hospital physicists	59	109	80	1.2	1.0	1.0	1.3	34
Those nursing patients with sealed sources in situ	12	216	95	4.4	3.6	3.3	3.8	121

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* less than 0.5

TABLE V Cont.

Occupational classification	Effective number of workers		Percentage of dose from photons of energy $>150keV_{eff}$	Average annual dose equivalent (monitor values) (mSv)	Average annual effective dose equivalent (mSv)	Average annual gonadal dose equivalent (mSv)		G.S.D. contribution (x 10^{-6} mSv)
	male	female				male	female	
Nuclear medicine								
Nuclear medicine technologists and assistants	241	225	45	0.4	0.3	0.5	0.3	33
Dentistry								
Dentists	320	135		0.1	0.0	0.1	0.1	4
Dental nurses and assistants	47	310		0.1	0.0	0.1	0.0	6
Chiropracty								
Chiropractors	82	6		0.2	0.1	0.2	0.0	1
Assistants	15	4		**	0.0	0.0	0.0	*
Veterinary								
Veterinary surgeons	129	35		0.2	0.1	0.2	0.0	3
Assistants	16	94		0.4	0.2	0.1	0.2	4
Receptionists⊖	73	283		0.2	0.1	0.1	0.1	2

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* less than 0.5

** less than 0.05

⊖ covering all medical and allied groups

TABLE V Cont.

Occupational classification	Effective number of workers		Percentage of dose from photons of energy >150keV$_{eff}$	Average annual dose equivalent (monitor values) (mSv)	Average annual effective dose equivalent (mSv)	Average annual gonadal dose equivalent (mSv)		G.S.D. contribution (x 10^{-6} mSv)
	male	female				male	female	
Industry and Research								
Users of X-ray analysis units, electron microscopes, etc	290	40		0.1	0.1	0.1	0.0	3
Users of enclosed installations[+] or "quality control" sources, e.g. package monitors, thickness gauges, etc	299	90		0.1	0.1	0.2	0.0	9
Users of open installations[++], including industrial radiographers	323	44	80	1.3	1.2	1.3	0.5	140
Users of radioactive tracers	274	84	70	0.5	0.3	0.3	0.0	14
Installation and maintenance engineers	101	2		0.2	0.2	0.1	0.6	2
Education								
Teachers or demonstrators	128	20		0.2	0.1	0.2	0.0	4
Students	133	103		0.2	0.1	0.1	0.1	7

[+] and [++] See footnote to Table IV.

TABLE VI. Multiplying factors for calculation of dose equivalents

Radiation type	Energy keV_{eff}	Multiplying factors for			
		effective dose equivalent		gonadal dose	
		male	female	male	female
30 kV Xrays	17	0.20	0.10	0.70	0.10
50 kV Xrays	20	0.30	0.10	0.75	0.15
75 kV Xrays	23	0.40	0.20	0.80	0.20
75 - 140 kV Xrays	33	0.60	0.40	0.90	0.30
140 - 180 kV Xrays	60	0.80	0.60	0.95	0.40
180 - 220 kV Xrays	70	0.80	0.65	1.00	0.60
230 - 250 kV Xrays	95	0.85	0.70	1.00	0.60
250 kV Xrays medium filtration	122	0.90	0.75	1.00	0.60
^{99m}Tc	140	0.90	0.75	1.00	0.60
300 kV Xrays heavy filtration	170	0.90	0.75	1.00	0.60
^{51}Cr	320	0.90	0.80	1.00	0.65
^{131}I	360	0.90	0.80	1.00	0.65
^{137}Cs, ^{192}Ir	660	0.90	0.80	1.00	0.65
^{226}Ra, ^{222}Rn	1200	0.90	0.80	1.00	0.70

TABLE VII. Age distribution of persons in specific occupations expressed as a percentage for each occupation (1975)

Occupational classification	Sex	Age range (years)						
		18-20	21-25	26-30	31-40	41-50	51-60	over 60
Radiology								
Radiologists and medical practitioners in hospitals	M	0	4	26	31	25	10	5
	F	0	6	11	17	56	10	0
Radiologists in clinics and private practices	M	0	5	3	26	31	26	9
General practitioners	M	0	3	29	25	23	14	6
Radiographers in hospitals and private practices	M	14	20	14	21	18	12	1
	F	21	30	15	17	13	3	1
Assistants, nurses, porters, etc	M	9	21	12	24	6	21	7
	F	13	34	18	13	15	7	0
Dermatology, radiotherapy and gynaecology								
Therapy radiographers	F	15	29	7	17	14	16	2
Those nursing patients with sealed sources in situ	F	19	21	18	16	13	13	0
Nuclear medicine								
Nuclear medicine technologists and assistants	M	3	26	24	29	15	3	0
	F	18	35	21	20	4	2	0
Dentistry								
Dentists	M	1	13	19	27	24	13	3
Dental nurses and assistants	M	11	46	11	22	8	2	0
	F	57	31	6	2	2	1	1
Chiropracty								
Chiropractors	M	0	2	15	36	31	14	2

TABLE VII Cont.

Occupational classification	Sex	Age range (years)						
		18-20	21-25	26-30	31-40	41-50	51-60	over 60
Veterinary								
Veterinary surgeons	M	0	11	30	34	19	6	0
Receptionists⊕	M	12	18	6	12	24	23	5
	F	23	13	9	26	23	6	0
Industry and Research								
Users of X-ray analysis units, electron microscopes, etc	M	3	16	19	33	21	6	2
	F	7	23	29	16	16	9	0
Users of enclosed installations[+] or "quality control" sources, e.g. package monitors, thickness gauges, etc	M	3	5	19	35	18	18	2
	F	3	8	18	50	17	4	0
Users of open installations[++], including industrial radiographers	M	4	16	23	33	13	11	0
Users of radioactive tracers	M	7	24	16	28	20	5	0
Installation and maintenance engineers	M	2	14	23	27	22	11	1
Education								
Teachers or demonstrators	M	1	13	38	36	10	2	0
Students	M	85	0	7	7	1	0	0

⊕ covering all medical and allied groups

[+] and [++] See footnote to Table IV.

TABLE VIII. Estimated life-time effective dose equivalent for radiation workers

Occupational classification	Average annual effective dose equivalent (mSv)	Predicted length of occupational exposure (years)		Estimated average life-time dose equivalent (mSv)	
		male	female	male	female
Radiology					
Radiologists in hospitals	0.9	40	30	36	27
Radiologists in clinics and private practices	1.7	40	30	68	51
Medical practitioners in hospitals	0.6	40	30	24	18
General practitioners	0.2	40	30	8	6
Radiographers in hospitals and private practices	0.5	40	30	20	15
Assistants, nurses, porters, etc	0.4	10	10	4	4
Maintenance engineers	0.2	40	30	8	6
Dermatology, radiotherapy and gynaecology					
Dermatologists	0.3	40	30	12	9
Radiotherapists and gynaecologists	1.8	40	30	72	54
Therapy radiographers and hospital physicists	1.0	35	30	35	30
Those nursing patients with sealed sources in situ	1.0	10	10	36	36

TABLE VIII Cont.

Occupational classification	Average annual effective dose equivalent (mSv)	Predicted length of occupational exposure (years)		Estimated average life-time dose equivalent (mSv)	
		male	female	male	female
Nuclear medicine					
Nuclear medicine technologists and assistants	0.3	40	30	12	9
Dentistry					
Dentists	0.0	40	30	0	0
Dental nurses and assistants	0.0	30	10	0	0
Chiropracty					
Chiropractors	0.1	35	25	4	3
Veterinary					
Veterinary surgeons	0.1	35	30	4	3
Assistants	0.2	30	5	6	1

TABLE VIII Cont.

Occupational classification	Average annual effective dose equivalent (mSv)	Predicted length of occupational exposure (years)		Estimated average life time dose equivalent (mSv)	
		male	female	male	female
Industry and Research					
Users of X-ray analysis units, electron microscopes, etc	0.1	25	10	3	1
Users of enclosed installations[+] or "quality control" sources, e.g. package monitors, thickness gauges, etc	0.1	35	30	4	3
Users of open installations[++], including industrial radiographers	1.2	30	25	36	30
Users of radioactive tracers	0.3	25	20	8	6
Installation and maintenance engineers	0.2	20	-	4	-

[+] and [++] See footnote to Table IV.

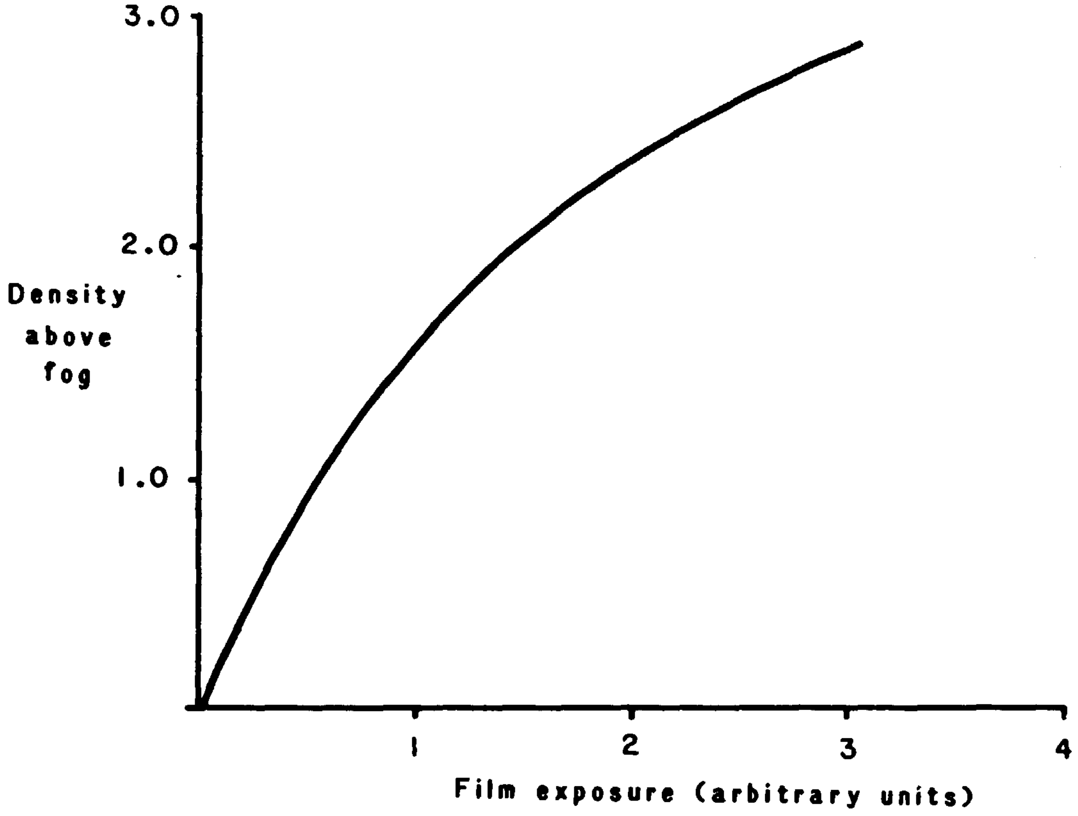


Fig 1. Variation of film density with exposure

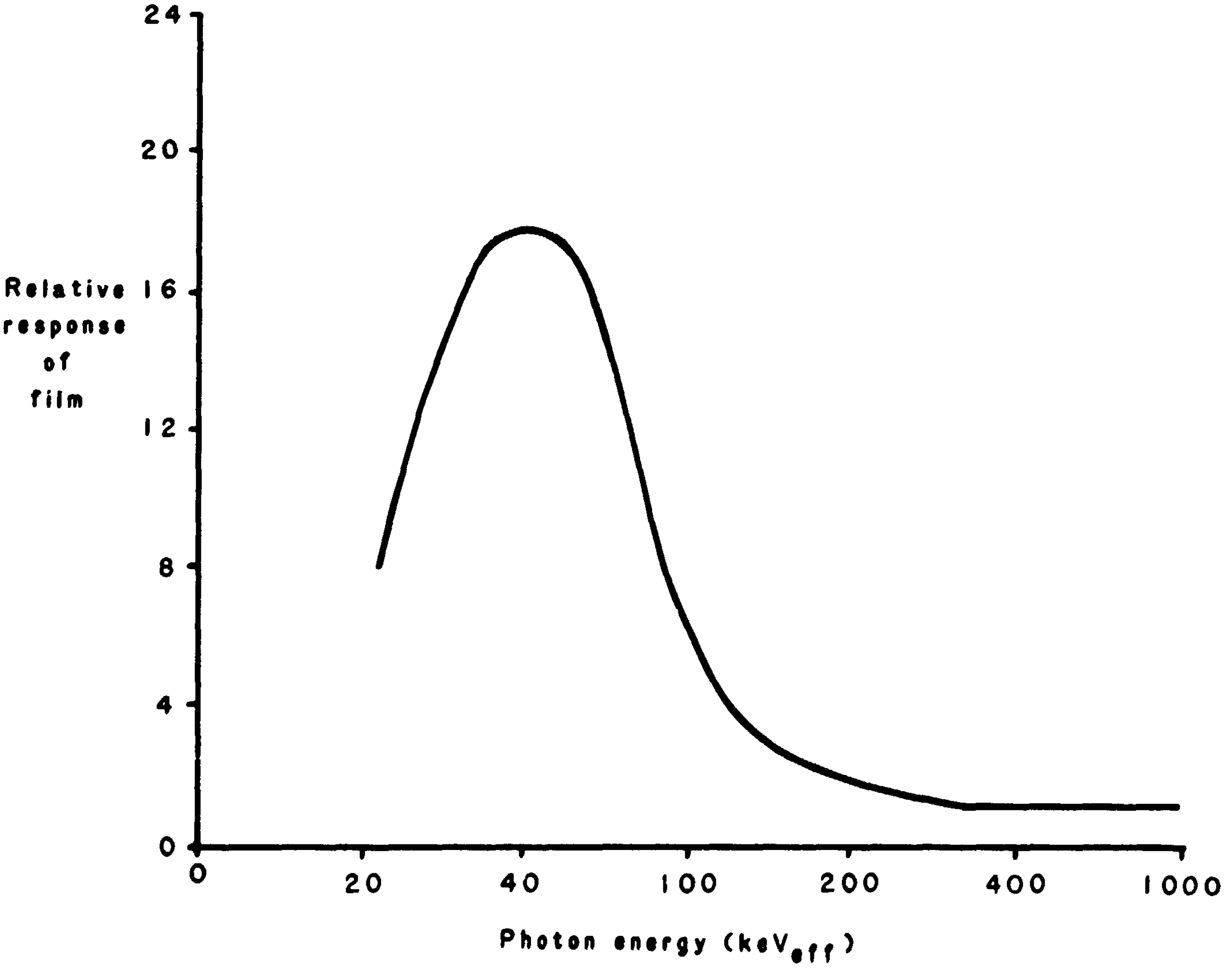
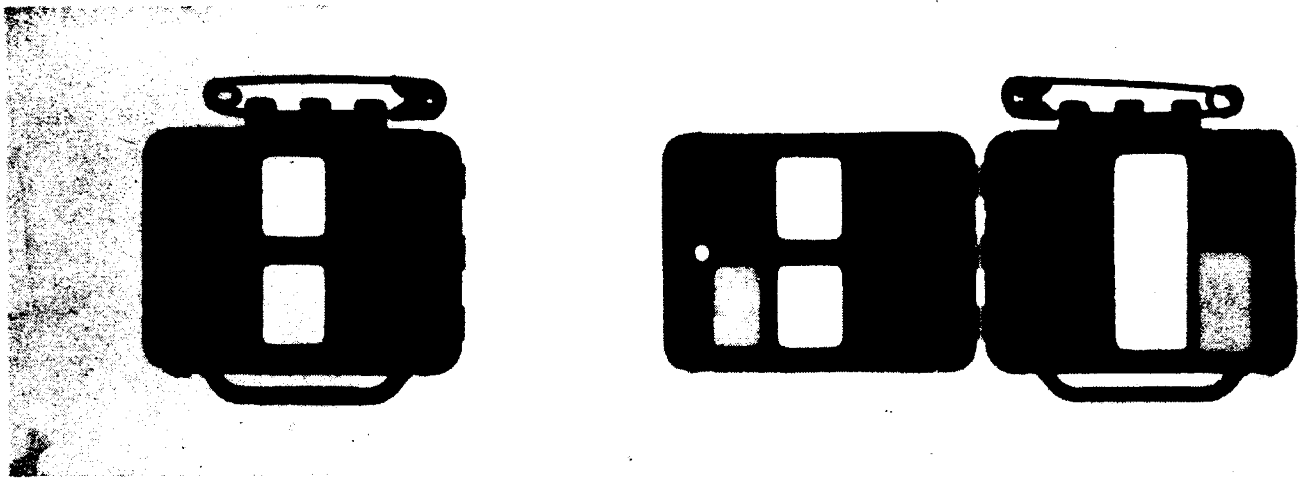
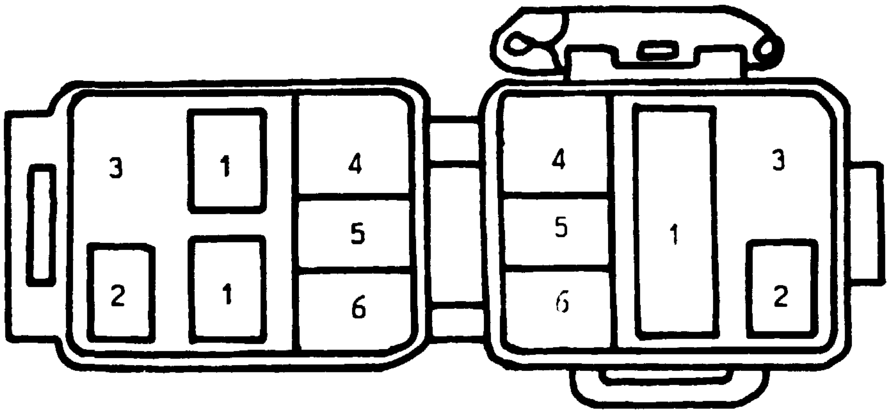


Fig 2. Film response vs radiation energy for a given film dose



(a) Closed holder

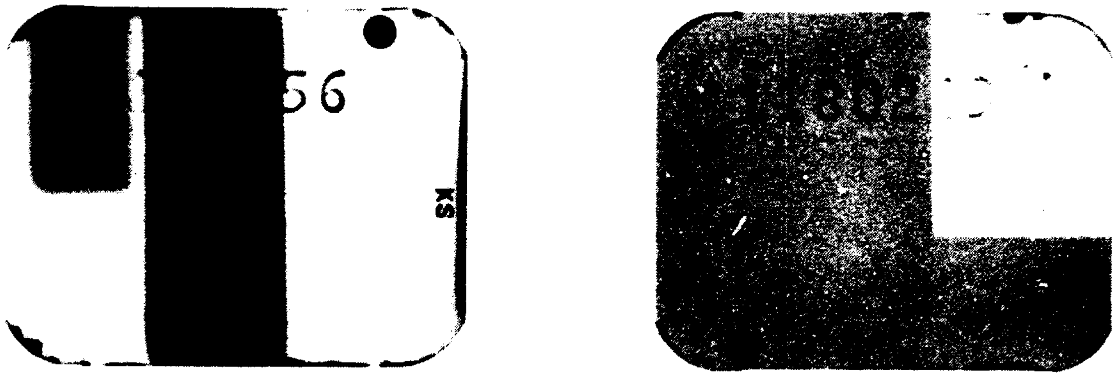
(b) Open holder



1. open window.
2. 50 mg/cm^2 plastic.
3. 300 mg/cm^2 plastic.
4. 1.0 mm dural.
5. 0.3 mm lead & 0.7 mm cadmium.
6. 0.3 mm lead & 0.7 mm tin.

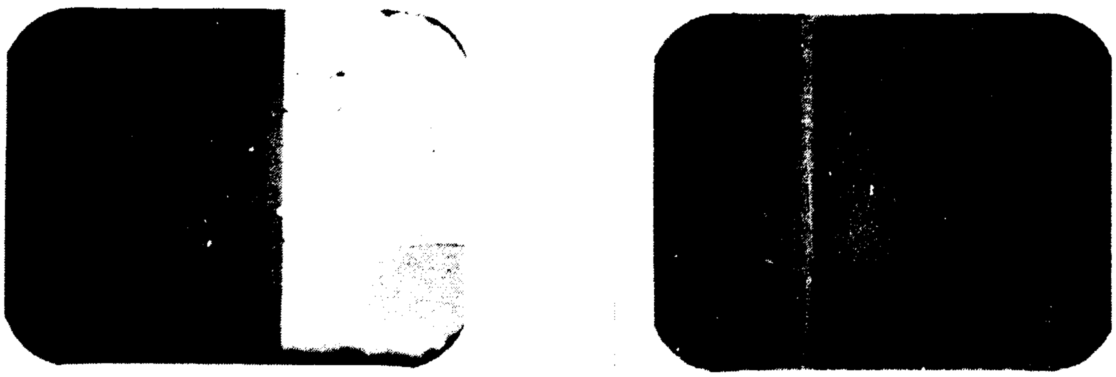
(c) Schematic diagram of different areas of holder

Fig 3. Film-badge holder used in ARL service



(a) βrays

(b) Diagnostic Xrays



(c) Mixture of βrays & superficial therapy Xrays

(d) Radium γrays

Fig 4. Appearances of developed films after exposure in holder to different radiations

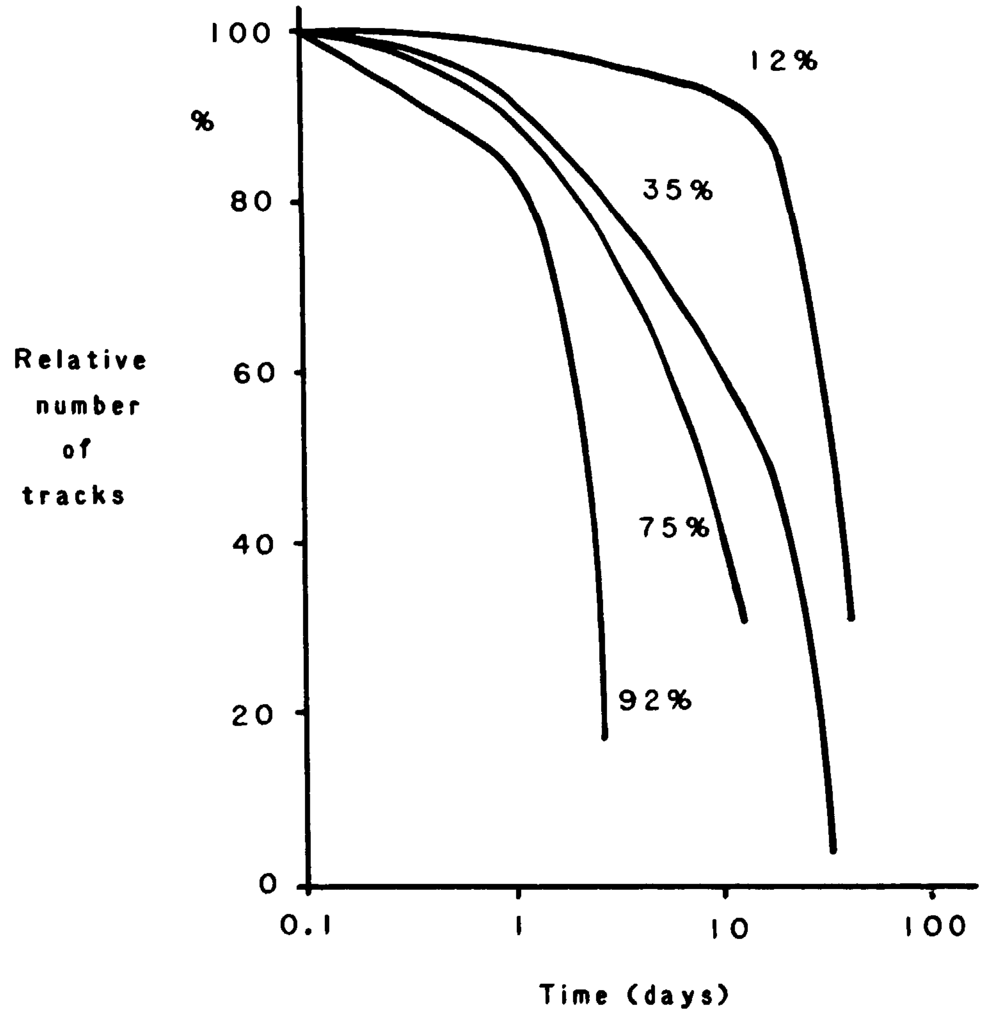
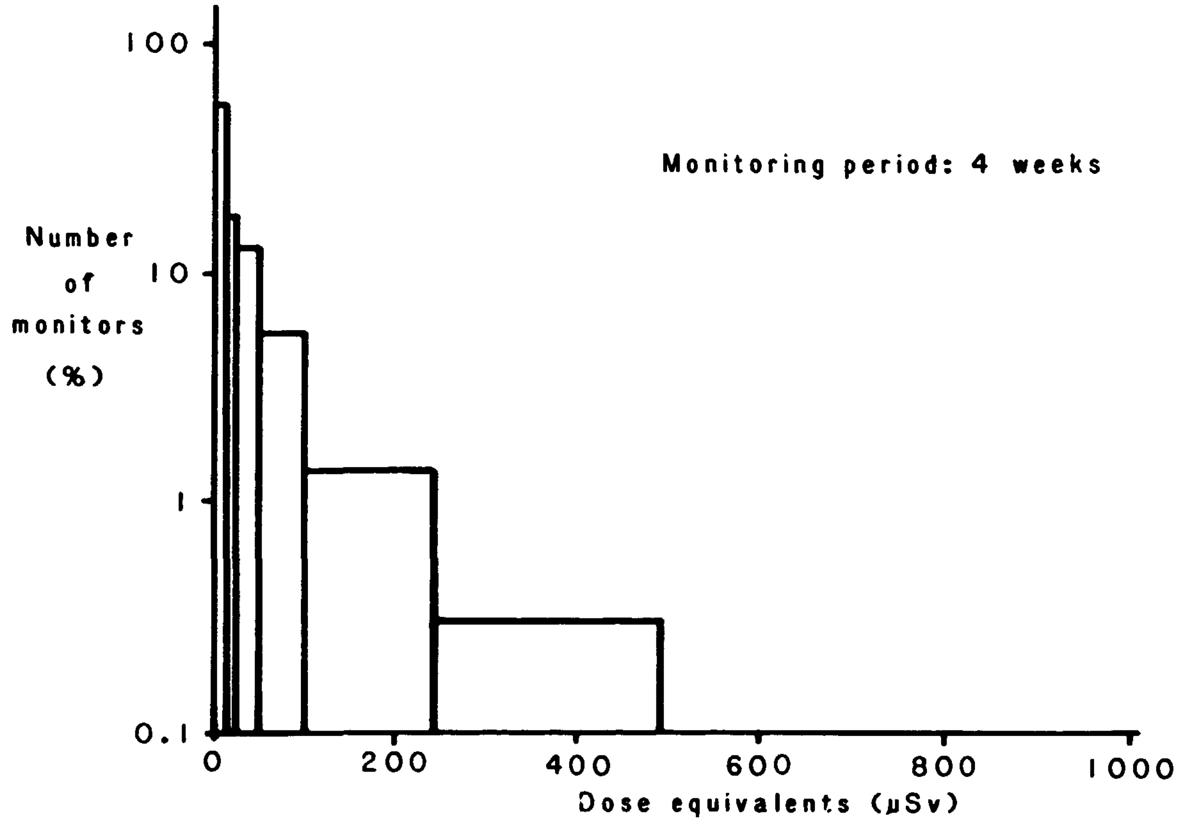
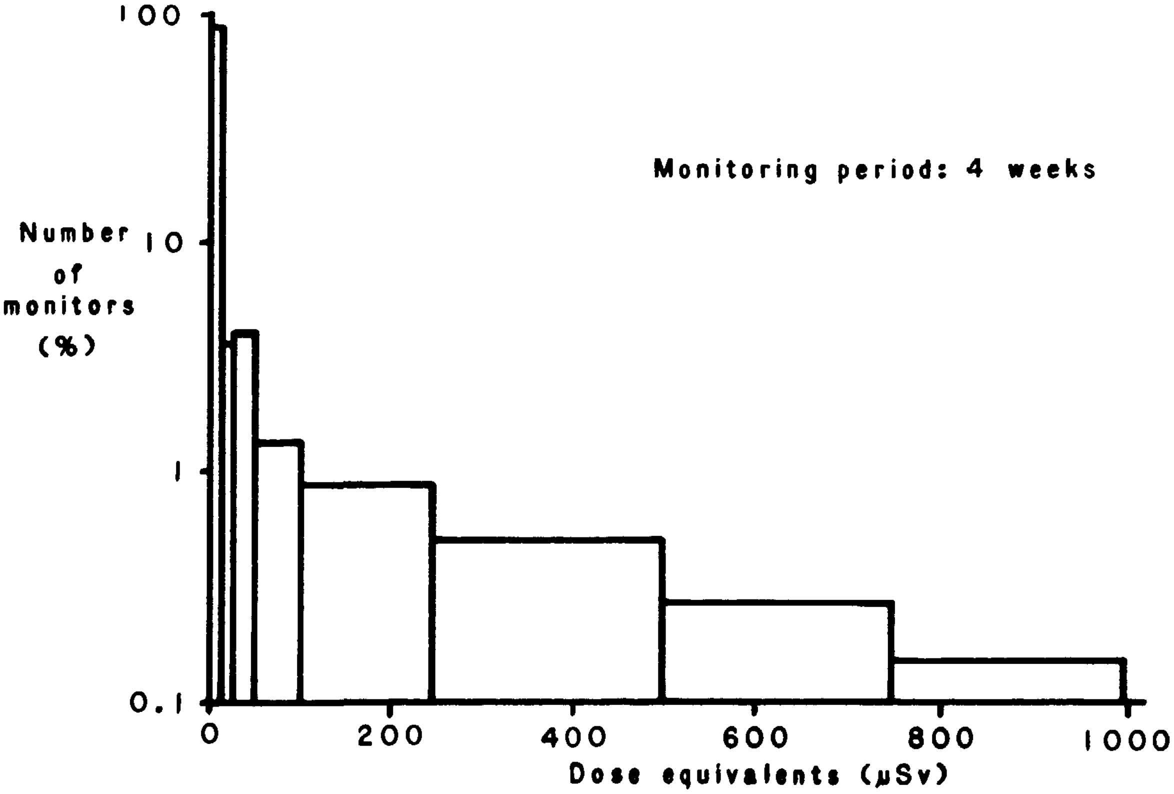


Fig 5. Fading of tracks in emulsion of neutron films as a function of time between exposure & development & of relative humidities of 12,35,75&92%

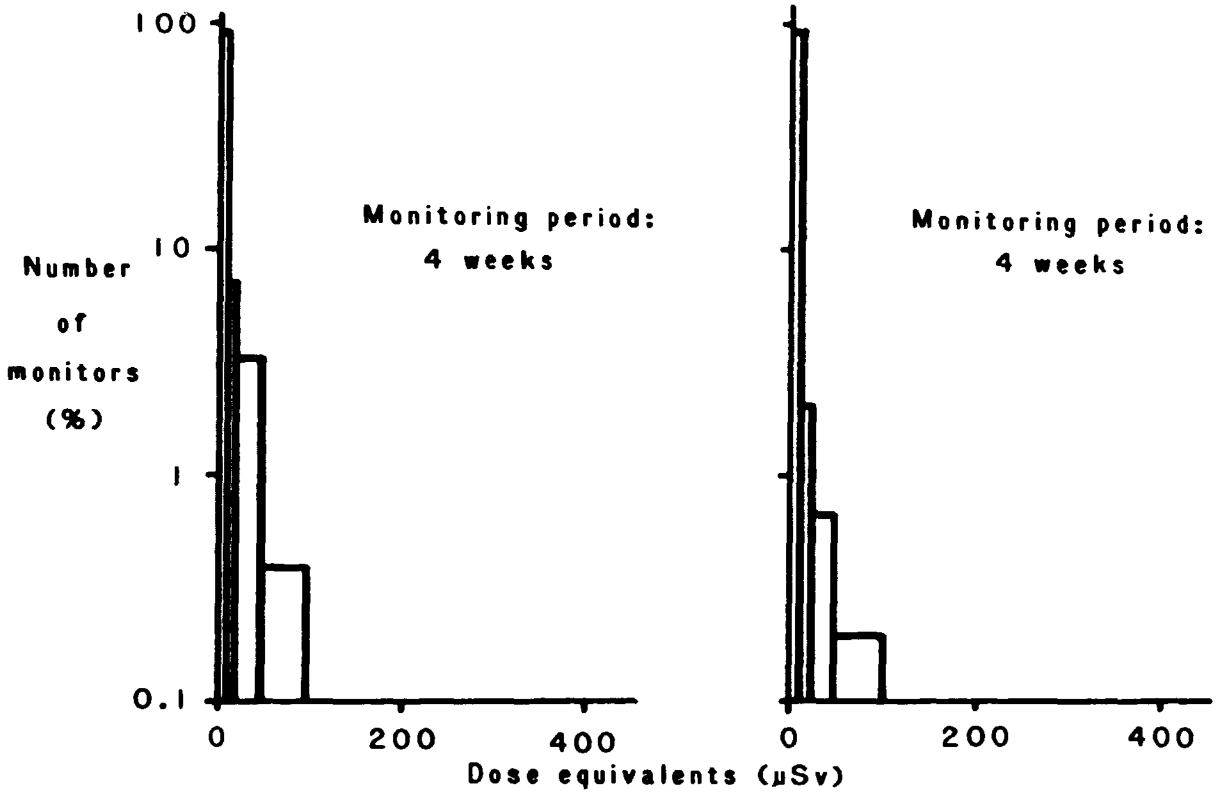


a) Radiologists, other medical practitioners & diagnostic radiographers



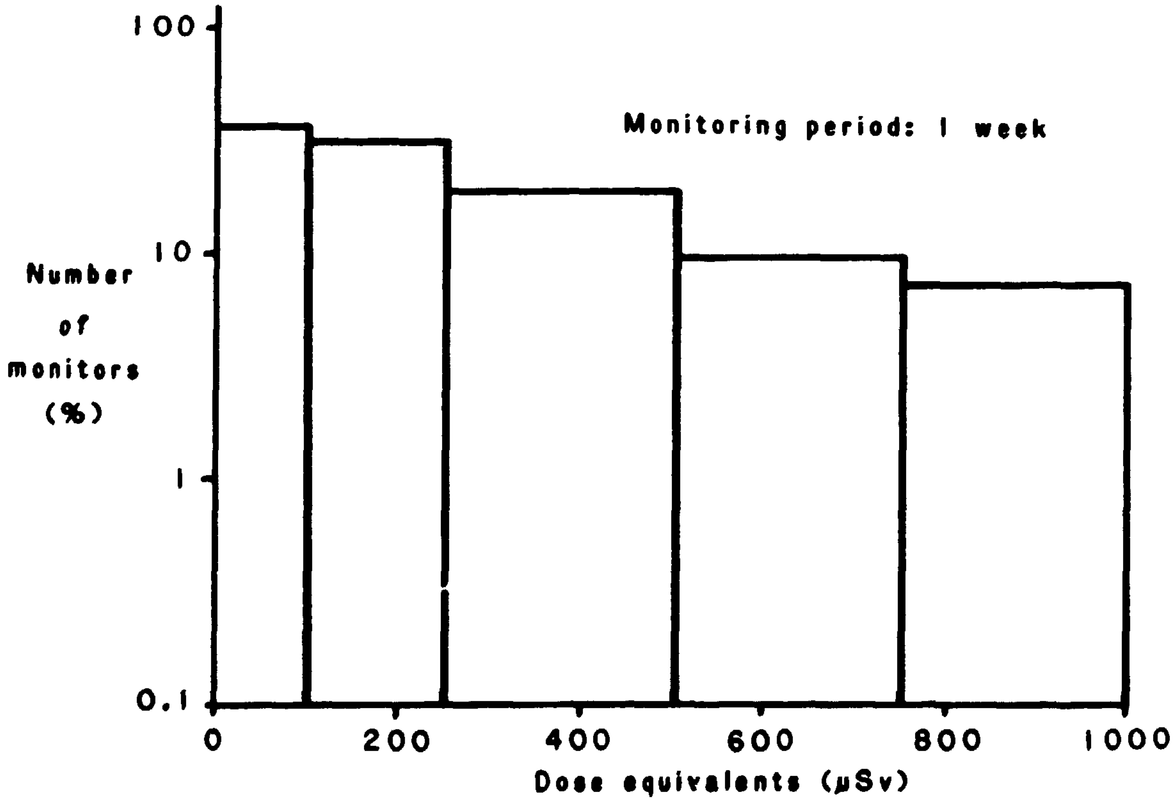
b) Nurses of patients with sealed radioactive sources in situ

Fig 6. Frequency distribution of doses received in selected occupational categories



c) Dentists

d) Researchers & industrial workers, other than radiographers



e) Industrial radiographers

Fig 6. Continued