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RADIATION PROTECTION INSTRUMENTATION FOR PERSONNEL DOSIMETRY, AREA AND ENVIRONMENTAL MONITORING

by

A.R. JONES

Presented at the Regional Seminar on the Preparation of Radiological and Environmental Protection for Nuclear Programmes in Latin America, Caracas, Venezuela, 21-25 November 1977

Chalk River Nuclear Laboratories

Chalk River, Ontario

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Instruments de radioprotection pour la dosimétrie du personnel et le contrôle zonal et environnemental*

par

A.R. Jones

Résumé

La dosimétrie du personnel donne divers problèmes au concepteur d'instruments. Par exemple, il n'est pas possible de déterminer de façon précise la dose absorbée provenant de rayonnements gamma externes au moyen de dosimètres individuels. Cependant, leur conception et leur calibrage devraient minimiser l'incertitude de l'estimation des doses. Plusieurs types de dosimètres individuels existent et leur performance est passée en revue à la lumière des exigences d'un instrument idéal.

Le contrôle zonal consiste à mesurer les rayonnements et la radioactivité dans une zone précise pour déterminer les risques encourus par les travailleurs. Les moniteurs de zone portatifs et fixes ont des limitations et leur emploi n'est que complémentaire. La nature des incertitudes concernant l'évaluation du risque est importante dans l'interprétation des données obtenues. On indique les exigences des instruments portatifs et l'on décrit la mesure dans laquelle on répond à ces exigences dans l'exemple donné.

Le contrôle environnemental constitue un exemple classique de la nécessité de distinguer le rayonnement par rapport au fond naturel. Lorsque l'on adoptera le principe selon lequel les doses environnementales doivent être maintenues aussi basses que possible, les doses gamma devant être mesurées pourront être inférieures aux fluctuations du fond naturel. Dans ce cas, il sera nécessaire de différencier entre les rayonnements naturels et les rayonnements créés par l'homme sur la base de la fluctuation temporelle et des différences d'énergie des photons.

Lorsque les doses environnementales sont plus grandes que les fluctuations du fond naturel, certains types de dosimètres thermoluminescents permettent d'avoir un système de mesure fiable et meilleur marché.

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A.R. Jones

ABSTRACT

Personnel dosimetry presents several problems for the instrument designer. For example, it is not possible to determine accurately the dose absorbed from external γ-radiation using personal dosimeters. However, their design and calibration should minimize the uncertainty of dose estimation. Several kinds of personal dosimeter exist and their performance is reviewed in the light of requirements for an ideal instrument.

Area monitoring is the measurement of radiation and radioactivity in an area to determine the hazards to which workers there are exposed. Portable and fixed area monitors suffer from different limitations and their use is complementary. The nature of the uncertainties in assessing the hazard is important in the intepretation of the data obtained. The requirements of portable instruments are reviewed and the extent to which they are met in one example is described.

Environmental monitoring provides a classic example of the need to discriminate against background. When the principle of keeping the environmental doses as low as reasonably achievable is adopted the γ doses to be measured may be smaller than the fluctuations in natural background. In this case it is necessary to discriminate between man-made and natural radiation on the bases of temporal fluctuation and photon energy differences.

Where permitted environmental doses are larger than the fluctuations in natural backgrounds, certain types of thermoluminescent dosimeters provide a cheaper and reliable alternative measuring system.

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Introduction

To attempt a discussion of all the instruments used in the three subjects listed in the title of my lecture would be futile. At best it would be a long catalog of instruments and techniques and it would bore you. Instead I will describe the nature of the problems faced by instrument designers and also outline some of the solutions and their limitations. From this I hope to draw realistic conclusions about what can, and cannot, be expected from instruments in personnel dosimetry, and in area and environmental monitoring.

Before considering each subject in turn we need to understand the role which instruments play in radiation protection.

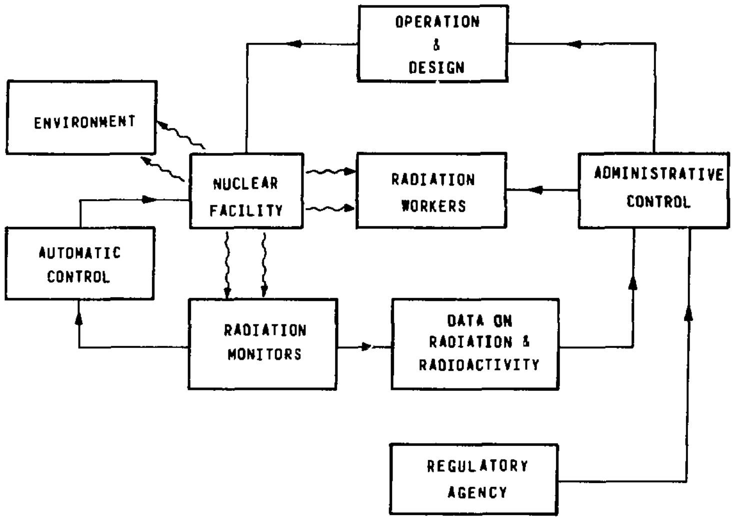

FIGURE 1. ROLE OF MONITORING INSTRUMENTS IN RADIATION PROTECTION

Figure 1 illustrates this role. The purpose of radiation protection is to reduce the harm done to radiation workers and the rest of mankind by man-made radioactivity to acceptable levels in relation to the benefits derived from nuclear facilities. For my purpose, the term "nuclear facility" includes all the different nuclear fuel cycle stages as well as research laboratories and hospitals which use or produce radioactivity. I also include machines which generate ionizing radiations without producing radioactivity.

Ionizing radiation which can affect radiation workers and the general public can also, in principle, be measured by instruments. The function of these instruments is to provide useful data about the radiation or the radioactivity which emits it. These data are generally required by agencies which governments

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appoint to regulate their nuclear industries. The data are used by those in charge of the nuclear facility to limit the dose to the radiation workers and the general population. This can be done in a number of ways:

- the work done by the radiation workers can be modified in terms of where and how long they work

- the nuclear facility can be operated in a different way

- the nuclear facility design can be modified and so can that of other facilities.

Personnel Dosimetry

For the purposes of this lecture the term Personnel Dosimetry means direct measurement on humans or their excretions to measure doses already absorbed or committed.

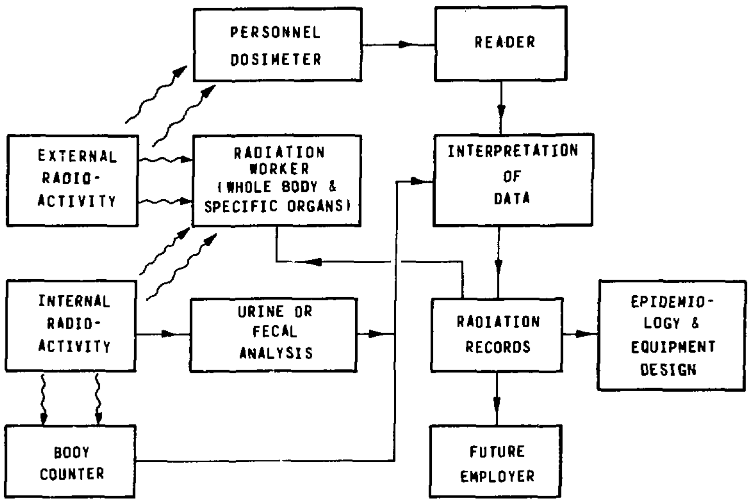


FIGURE 2. PERSONNEL DOSIMETRY

Figure 2 illustrates how radioactivity, internal and external, which irradiates humans is measured and how the measurements are used. In the figure only radiation workers are considered because members of the public within the environment are not generally subjected to intensive personnel dosimetry. In principle they can be, although the instruments must be more sensitive.

Internal radioactivity can be measured by urine or fecal analysis or, more directly, with a whole body or organ counter. Although urine and fecal analysis is more indirect it uses less of workers' time and must be used if the activity does not emit photons. When the activity and its time of uptake have been estimated, its distribution determined and the radionuclide identified, an estimate of integrated and committed dose is made.

External radiation is measured by a dosimeter worn by the person and its reading must be interpreted in terms of dose to the whole body or specific organs. This estimation of dose is then added to the radiation worker's record along with the dose estimate from internal activity. Generally the largest component of dose is absorbed from external radiation. However, uptakes of the radioiodines and tritium do give rise to significant doses. The data in these records may be used in four ways:

- to limit the radiation worker's future exposure
- to inform a future employer of the worker's radiation history
- to initiate modifications in the design of equipment to reduce exposure to all workers using it
- to estimate the effects of low-level chronic radiation in epidemiological studies to refine regulations about radiation exposure.

Up to this point, the application of monitoring instruments to radiation protection might seem quite straightforward; but this is not always so. I will illustrate the point by reference to personnel dosimetry for γ-radiation.

In 1966 ICRP recommended the same dose equivalent annual limit, 5 rem (50 mSv), for the whole body, the bone marrow and the gonads,[(1)]. Moreover, this is the most restrictive limit for radiation workers. In 1977, the recommendation was changed so as to apply to all the organs using appropriate weighting factors, which still gives prominence to these same organs[(2)]. Clearly, the function of the personal dosimeter is to measure this dose equivalent. Figure 3 shows how the doses absorbed in two of these organs, the bone marrow and the testes, vary in terms of the exposure to the body at the place where a personal dosimeter is worn. As can be seen the relationship between these two quantities varies greatly depending upon the energy of the photons and upon their direction of incidence and is quite different for the two organs.

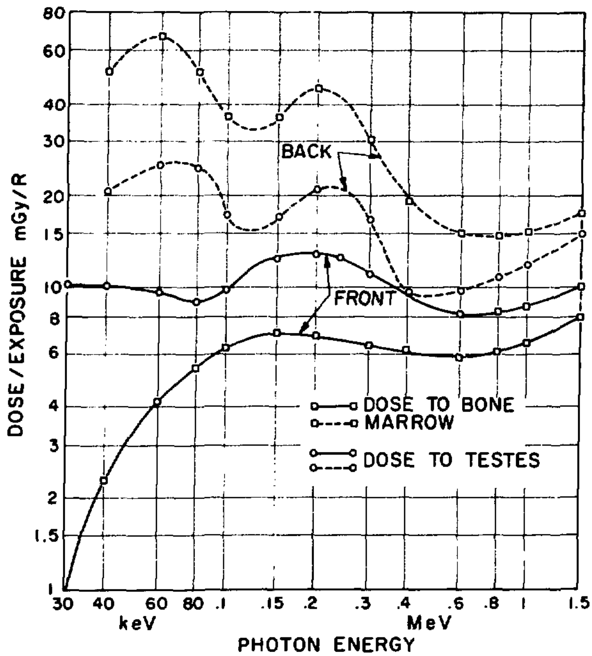


FIGURE 3. DOSE ABSORBED IN BONE MARROW AND TESTES PER EXPOSURE TO PERSONAL DOSIMETER

1 Gy = 100 rad

An ideal dosimeter would provide data to allow calculation of the doses to the various critical organs regardless of the photon energy and direction and the distance of the source. At present it is hard to conceive of such a dosimeter. In practice a choice must be made of an energy dependence and a calibration factor which, in the most probable situations, will not lead to a serious underestimate of dose to the critical organs or whole body. To choose the curve corresponding to the dose to the bone marrow, with radiation from behind, would certainly be safe. However, in the more likely irradiation direction this would overestimate the dose by a factor between 2 and 4. In any case, whichever set of calibration factors is chosen it is clear that the exposure to the personal dosimeter can give only a very approximate indication of dose to these critical organs. I draw your attention to these fundamental uncertainties in personnel dosimetry to put in perspective the question of instrumental accuracy.

It is clear that great accuracy in personal dosimeters is meaningless in terms of measurement of dose. Its real value lies in the ability it affords to check the reliability of the dosimetry service and to promote confidence in it.

Required Characteristics of Personal Dosimeters

1. Adequate dose equivalent range 10^{-2} - 10^{3} rem (10^{-4} - 10 Sv)

2. Adequate energy independence

3. Discrimination between different radiations

4. Discrimination between dose equivalents absorbed in different organs

5. Provides significant data in a form usable by computers

6. Adequate accuracy

7. Rapid read-out when needed

8. Low fading during exposure period

The first requirement of range of dose equivalent is set by the uses to which the output data are put. Doses as low as 10 mrem (10^{-4} Sv) are not by themselves very significant. However, if repeated every two weeks a life-time total $\sim$ 10 rem (0.1 Sv) would result and this is too high if it can be easily avoided. The data might also be useful for epidemiology. For whole body radiation, measurements of dose equivalent up to 1000 rem (10 Sv) are useful but above this level the fate and treatment of a person would probably be the same. However, for measurement of superficial doses at least another decade is needed because a dose equivalent of 10 krem (100 Sv) would be survivable and more probable than the same penetrating dose equivalent.

The curves shown in Figure 3 show the importance of energy response for γ-ray dosimeters. The energy response is even more important in a neutron dosimeter. The body changes the direction, number and energy of incident neutrons in an energy dependent manner. In addition, the ratio of dose equivalent to dose varies over a range of 2 - 10[4] according to energy. A suitable personal dosimeter which can be used to accurately measure doses, in the absence of knowledge about the neutron spectrum, does not yet exist.

If a dosimeter could give a correct estimate of dose equivalent regardless of which ionizing radiation is absorbed there would be no need to distinguish between radiations for strictly dosimetric purposes. Failing that, the dosimeter should respond correctly to one radiation and be insensitive to all others. Thus by having a set of dosimeters the dose equivalent can be correctly summed. In fact it is not possible to distinguish clearly between β and γ radiations since in both cases dose is absorbed by slowing down electrons. In this case it is more practical to distinguish between the surface (skin) and penetrating (whole body and internal organs) doses regardless of whether they are due to β- or γ-rays. Apart from this, it is not usual to make further distinctions between doses absorbed in different organs for β- and γ-rays.

The data obtained from dosimeters must be recorded in units of dose equivalent. Because personnel dosimetry involves quite complicated bookkeeping it is very desirable that the data can be fed to a computer automatically. In practice this means a reading device with either a direct link to a computer or an output on magnetic or punched paper tapes.

For reasons given before, it is difficult to assign significance to an absolute accuracy of organ dose which is better than 20%. However, to check the operation of the dosimetry service a reproducibility of 10% is desirable. Also the variation between dosimeters should be less than 10% or their individual variation known and corrected to less than 10%.

It is desirable for all dosimeters used in a service to be read and the data interpreted without undue delay to keep those responsible for radiation protection up-to-date. Also, there must be a capability for reading individual dosimeters very quickly to deal with emergencies.

Personal dosimeters are worn for periods varying between a few minutes and three months, according to the kind of use. Fading should not add significant error during the maximum period over which they might be used.

The following table lists some types of dosimeters and some important characteristics. Ideally, a dosimeter, after exposure and reading, should give the user the choice of resetting it to zero, or not, before reuse. Only electronic dosimeters or direct reading ion chambers give this choice. The more widely used film and thermoluminescent dosimeters (TLD's) do not really provide this choice. With films, developing prevents further use. TLD's are reset to zero after reading and the previous dose can only be re-read with reduced accuracy and sensitivity after uv irradiation. Although there has been much controversy as to the merits of reusability vs. re-readibility it has not prevented the increased use of TLD's.

Personal Dosimeter Types and Characteristics

Dosimeter Type	Radiation Measured	Reusable	Re-readable	Re-settable
Photographic Film	γ, β, n	No	Yes	No
Thermoluminescent (TLD)	γ, β, n	Yes	With difficulty	Yes
Thermally Stimulated Electron Emmission	γ, β, n	Yes	No	Yes
Radio Photoluminescent	γ, β, n	Yes	Yes	After Annealing
Track Etch	n	No	Yes	No
Direct Reading Ion Chambers	γ, β, n	Yes	Yes	Yes
Activation Dosimeters	n	-	-	-
Electronic Dosimeters (Ion Chamber or GM Counter)	γ	Yes	Yes	Yes
Silicon Diodes	n	Yes	Yes	No

Of the first four listed dosimeters, used for routine $\beta\gamma$ dosimetry and all of the passive kind, the TLD's most closely match the required characteristics which I have discussed and, I believe, this accounts for their increasing use.

Neutron dosimeters have varying characteristics in terms of energy response and dose equivalent range. The interpretation of the data in terms of dose equivalent is even more difficult than with $\beta\gamma$ dosimeters. In accelerator environments neutron dosimeters are often used for routine measurements. Around reactors and fuel processing plants, although widely carried, they are generally restricted to accident dosimetry.

The direct reading ion chamber has been used for a long time and it possesses one important property - it can be read by the user at any time and for this reason is often used to control exposure. Its usefulness is limited because it can cover only about one decade of dose range and it cannot draw attention to a hazardous accumulation of dose.

It is these limitations which make me believe that electronic dosimeters will play a more important part in future.

Figure 4 shows the outside of a pocket-size dosimeter which has simple functions:[5]

- to warn the wearer when a preset gamma dose has been accumulated

- to warn the wearer of a hazardous dose rate.

In addition the dose absorbed can be estimated after use. It can be used over a wide range of dose rates - from background up to 100 rad/h (1 Gy/h) - and, because its memory is digital, it does not suffer from fading.

Figure 5, which shows the interior, illustrates several points:

- the electronic circuitry, even though only partly integrated, takes up a small fraction of the space

- the loudspeaker is large because it is difficult to make one that is small, loud and efficient

- the volume given up to the battery is another limitation on miniaturization and this can only be reduced by decreasing the power consumption of circuits, visible displays and loudspeakers.

Electronic dosimeters are already available with numerical display of the integrated dose. With available techniques much more versatile dosimeters could be designed with the following features:

- numerical display of dose over a wide range

- numerical display of dose rate over a wide range

- visible and audible warnings settable at desired levels of dose and dose rate

- immediate transfer of data for processing.

At the end of each work shift such dosimeters could be automatically tested and their batteries recharged.

Area Monitoring

"Area Monitors" is a term often applied to fixed gamma or neutron monitors but I intend to deal with a wider meaning. The purpose of area monitoring is to determine whether an area can be safely occupied and if so for how long. Figure 6 shows how it is used.

FIGURE 4. WARNING DOSIMETER

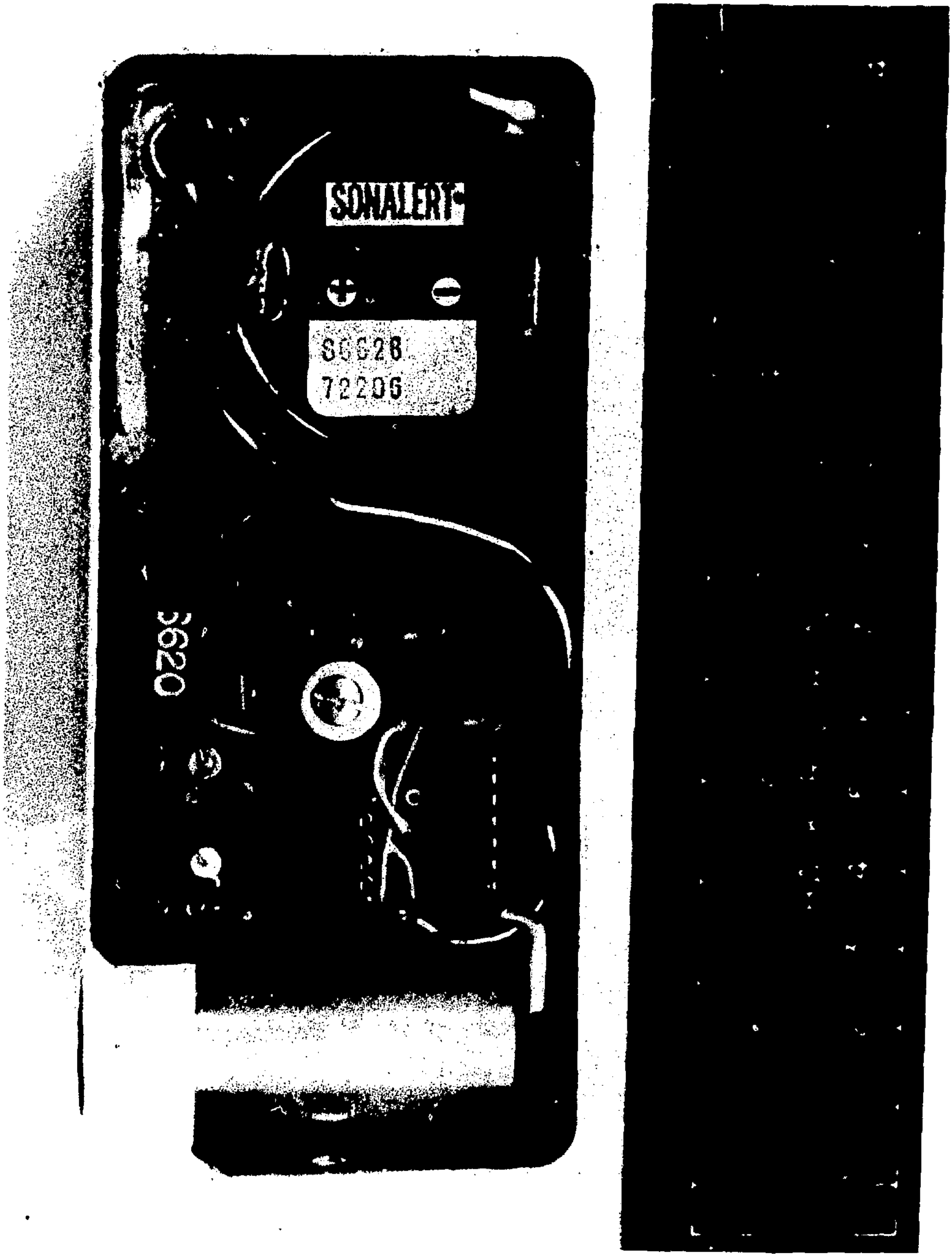


FIGURE 5. WARNING DOSIMETER - INTERIOR

Radioactivity contained in a monitored area can irradiate a radiation worker in that area both externally and internally, if it is borne by the air which he breathes. Similarly radioactivity irradiates the detectors in portable survey meters and fixed area monitors.

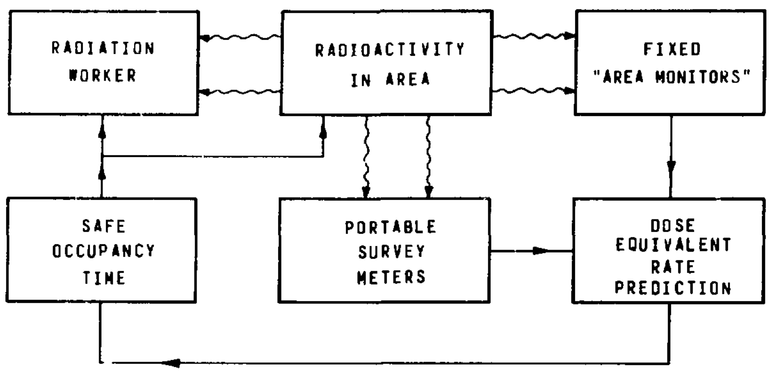


FIGURE 6. AREA MONITORING INSTRUMENTS

The two kinds of instruments have quite distinct functions which are complementary.

Portable survey meters are used to assess the variations in dose rate which can occur within the monitored area. A variation over two orders of magnitude is not exceptional. However, survey meters are often used only before it is decided to allow the use of an area and then give no information about subsequent increases in dose rate which can change the situation from safe to hazardous.

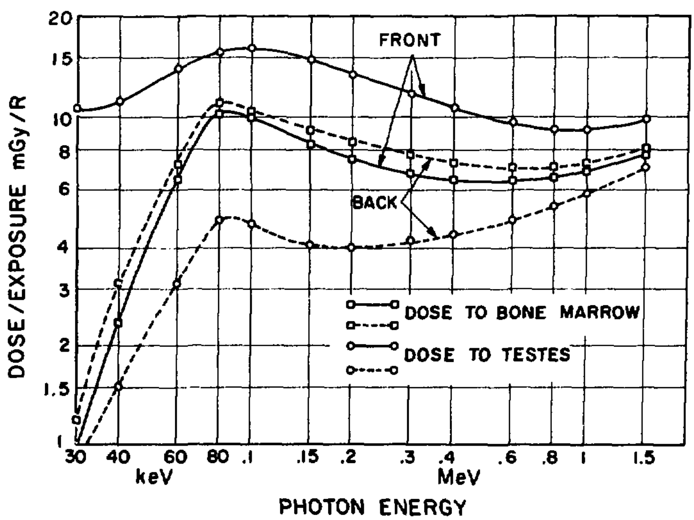
Fixed area monitors do provide information about time variation of dose rate and therefore deal with the problem which I have just mentioned. In addition, they can show when the dose rate in an area has fallen sufficiently to permit entry. However, unless the area is provided with a large number of radiation detectors, fixed area monitors give little indication of the variation of dose rate over the monitored area.

Fixed area monitors may be in the form of dose rate meters (γ-rays or neutrons) or they may measure the activity (alpha and beta) in the air.

Whether portable survey meters or fixed area monitors, of either kind, are used their output must be interpreted in terms of dose equivalent rate at the point or points in the monitored area which the radiation worker would occupy. From this follows a decision to admit the worker to the area or to require evacuation. If the area can be safely occupied, the question of how long must be answered in terms of the estimated dose rate equivalent. However this quantity is estimated, it will be appreciated that there will be large discrepancies between the dose equivalents measured by personal dosimeters and the estimates derived from area monitoring. For this reason, considerable safety factors are used.

If the predicted dose rates are unacceptably high, steps will generally be taken to remove the radioactivity or improve its shielding.

The problem of relating dose rates measured by area monitors to the dose absorbed by radiation workers, at the same place, is illustrated by Figure 7[3]. Doses measured in the bone marrow and testes sites in a phantom are plotted against energy as a function of the free-air exposure. An ideal area monitor or survey meter would have the response corresponding to the upper curve representing the dose absorbed in the testes when irradiated from in front. Thus it would correctly predict the dose in this situation and overestimate it in the situations represented by the lower curves. It is also desirable that the dose registered by the personal dosimeter should be correctly estimated or, failing that, overestimated. Otherwise radiation workers would be overexposed at least in terms of the doses recorded by the personal dosimeters which provide the data for the record of radiation history.



1 mGy = 100 mrad

FIGURE 7. DOSE ABSORBED IN BONE MARROW AND TESTES AS A FUNCTION OF FREE-AIR EXPOSURE

Required Characteristics of Fixed Area Monitors

1. Adequate dose equivalent rate range 1 mrem/h - 100 rem/h (10 μSv/h - 1 Sv/h)

2. Adequate speed of response in relation to dose equivalent rate

3. Adjustable alarm levels (visible)

4. Provision for recording output

5. Output data available at control centre and in monitored area

6. Self checking

7. Adequate coverage of area

8. Adequate accuracy

9. High dependability

The dose equivalent rate range should go at least as high as the maximum rate in which workers would be permitted to stay in the area even for a short time. It should at least go down to the minimum rate which is significant from the viewpoint of hazard or analysis of plant operation. If their function is monitoring the concentration of α or β emitters in air the same considerations apply.

The speed of response should be fast enough that workers in the area should not be significantly exposed during the response. This means that the speed of response can be quite low at low dose equivalent rates, which is an advantage from an engineering viewpoint.

The alarm levels should be adjustable when authorized by those responsible for radiation protection. However, the chosen level should be known to those working in the monitored area and, preferably, there should be a visible indication of the alarm level.

An output to drive a recorder or to be fed to a computer is required. A record of dose equivalent rate, or concentration of activity in air, is needed for the analysis of excessive levels or to furnish proof of their absence.

Area monitors provide data about the quantity measured and give alarm signals, and both kinds of information are needed at the central control and in the monitored area. The alarm signals may be required also for automatic control, e.g., for shutting down a radiation source or closing interlocks for denying access to a monitored area.

To reassure users of the monitors, radioactive sources should be available for checking every part of the monitor from detectors, through electronics to the display. These sources should, preferably, be deployed by remote command from the central control unit.

Because of the variation of dose equivalent rates and activity concentrations in the monitored area there should be enough detectors to reduce the uncertainty due to the variation to an acceptable level.

For reasons already given, absolute accuracy is poor. However, constant sensitivity is important so that checking with a constant source can more easily reveal trouble early on.

High dependability is most important to give confidence to users of the monitored area that they will be certainly informed of a hazard and will not be falsely alarmed.

<u>Required Characteristics of Portable Survey Meters</u>

1. Adequate dose equivalent rate range 1 mrem/h - 100 rem/h (10 μSv/h - 1 Sv/h)
2. Adequate speed of response for searching
3. Alarm operative at all times
4. Adequate accuracy
5. High dependability
6. Versatility
7. Simplicity of Displays and Controls
8. Unambiguous display
9. Remote operation
10. Trend indication for searching
11. Portability

The requirements for dose equivalent rate range are similar to those for fixed area monitoring. Above the upper limit of range, and up to the maximum credible dose rate it is important that an off-scale indication be maintained to avoid a very dangerous ambiguity.

Fast response is needed because survey meters are used for searching for variations in the dose rate. Both economics and safety dictate that this should be done as soon as possible. Considerations of stability and statistics often limit the speed of response at low dose rates.

Many radiation 'incidents' occur when they are not expected, for example when a survey meter is not in use. It is, therefore, desirable that the instrument remain in operation at all times and capable of providing an audible and visible warning of a dangerous dose rate. This is, of course, usurping the function of a fixed area monitor but radiation workers must often go where area monitors are not in use.

Again, the accuracy over an adequate energy range must be enough in relation to the uncertainties of relating the measurement to the dose absorbed by the worker. Reproducibility helps to produce confidence in those using the instruments. A large source of uncertainty in predicting actual doses is due to variations in the distance to the source. For this reason a survey meter which is carried at the same place as a personal dosimeter is likely to predict the registered dose far more accurately.

Dependability is just as important for portable monitors but more difficult to achieve. The monitors must be both strong and light. My own analysis of failures in portable instruments used at a typical nuclear research laboratory strongly suggests that most failures are due to mechanical shock - which is hardly surprising in view of their treatment.

Versatility is important because if a number of different kinds of instruments are needed to survey different radiation hazards (e.g. from both β- and γ-rays) surveying becomes more complex and time consuming.

The controls should be few and easy to operate and the displays should be simple and unambiguous to read. I favour liquid crystal numerical displays which need consume little power and can be read under a wide range of lighting conditions. They do not generally operate properly below about $0^{\circ}C$ but this is not a serious limitation in some climates.

Because the displays should be quite unambiguous, numerical displays are better than analog meters because they can be designed so that a shift in range is clearly shown by the location of the decimal point.

At the higher dose rates, it is sometimes desirable to be able to set the survey meter down and read the display from a distance to reduce exposure to the user. Again, large numerical displays are better for this purpose.

Since survey meters are used for locating regions of relatively high or low dose rate it is desirable that the trend towards higher or lower dose rates be indicated either audibly or visibly or both.

Small size and weight should not need mentioning, but they do, because many bulky, heavy survey meters are made. Portability is an essential feature because a good but heavy instrument left behind in an office is of no value.

Figure 8 is a photograph of a βγ Survey Meter designed with these requirements in mind[6]. It covers a wide range of γ-dose-rates from 1 mrad/h - 100 rad/h (10 μGy/h - 1 Gy/h) and the readings are displayed with a three range, three digit numerical panel meter. The display is on only when being used so that battery energy is conserved. At all other times the rest of the circuitry is powered to provide an audible and a visible indication of hazardous

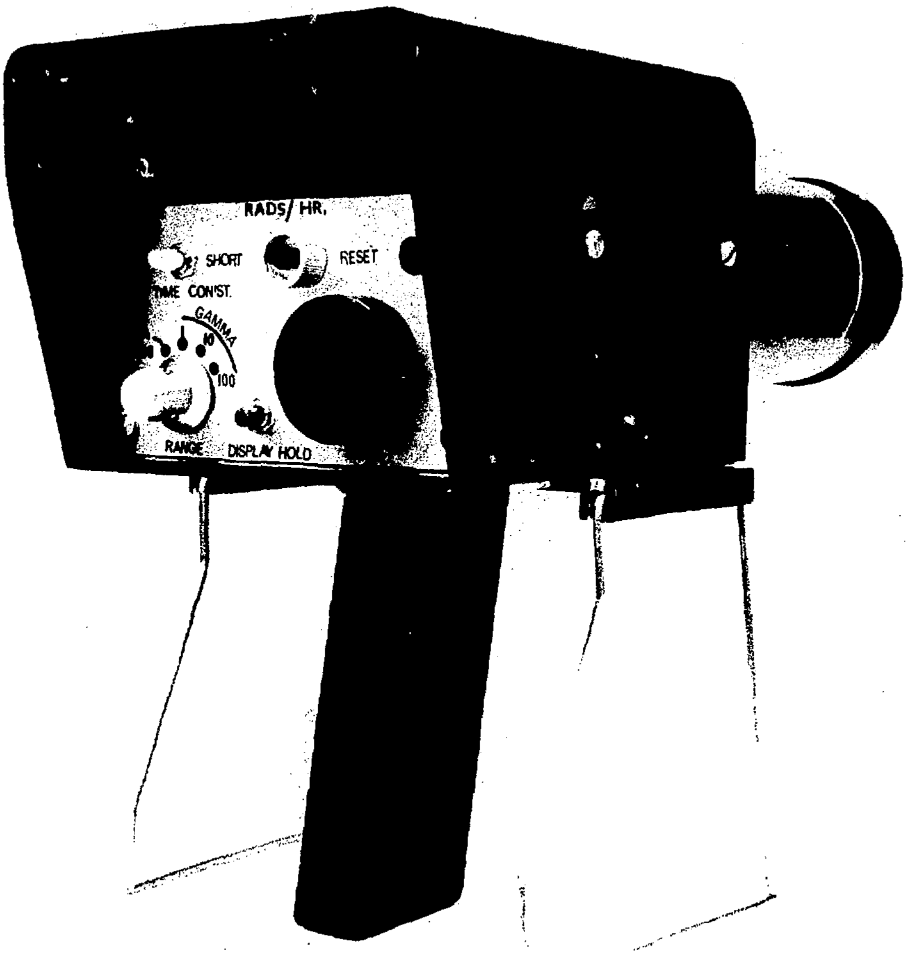


FIGURE 8. $\beta\gamma$-SURVEY METER

dose rates and when a preset dose has been exceeded. β dose rates can also be monitored up to 100 rad/h (1 Gy/h).

Environmental Monitoring

For my purpose I will define the environment as the world outside of a nuclear facility. The environment contains a large amount of natural radioactivity and a small amount of man-made radioactivity which may have originated within the nuclear facility. It is with this second, smaller quantity that we are directly concerned. Background activity is of concern because it makes more difficult the problem of distinguishing and measuring man-made activity and dose rates due to it.

Figure 9 shows the part played by monitors in solving this problem. Within the nuclear facility itself there are very sensitive monitors of release of radioactivity to the environment but there are many uncertainties in following, quantitatively, the pathways that the radioactivity will take. Moreover, such monitors do not detect unknown release routes. It is for these reasons that direct monitoring of the environment is also needed.

Experience with well-managed nuclear facilities has shown that environmental dose rates due to release of activity can be

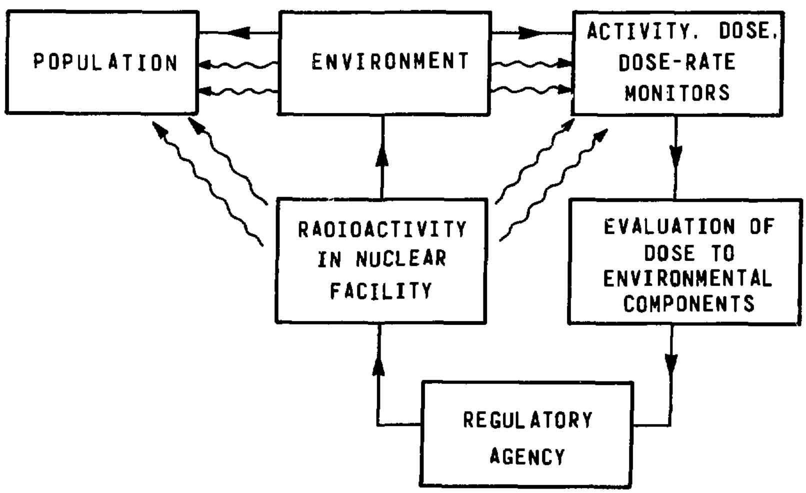


FIGURE 9. ROLE OF ENVIRONMENTAL MONITORS

kept far below levels recommended by ICRP(1) for the population at large. As a consequence, in some countries the concept of keeping doses as low as readily achievable(7) becomes embodied in regulations and tied to a specific level. From the monitoring viewpoint this "paints us into a corner". Sensitive effluent monitors may indicate that this recommendation is being followed. To ensure that this is so by directly monitoring the environment is another story, for the released radioactivity will have been diluted and mixed with naturally occurring radionuclides.

The environmental radioactivity contributes to the population dose both via ingestion and external radiation. Similarly, the released radioactivity can be monitored in terms of its concentration or directly in terms of external dose rate.

It should also be remembered that the general public and monitors near a nuclear facility can also be directly irradiated by inadequately shielded penetrating radiations from the nuclear facility itself.

By measuring the radioactivity in food, water, air and in human populations a more direct and reliable prediction of dose from ingested radioactivity can be made. However, there are two main problems:

- the low levels at which the measurements must be made

- discrimination between man-made and natural radioactivity.

Similarly, the environmental dose and dose rates due to external radioactivity can be measured and in this case the problem of distinguishing between man-made and natural sources may be even more difficult.

The total dose estimates are generally reported to a regulatory agency for comparison with the limits laid down for the environment around the nuclear facility. Its continued operation may depend upon the dose rates to the general population being satisfactorily low.

To properly distinguish between man-made and natural doses it is desirable to have the system of environmental monitors in place and working for some time before the nuclear facility begins to operate. Thus, information will be obtained on natural radioactivity and dose rates and the normal fluctuations in these quantities.

Figure 10 shows how environmental radioactivity is monitored. Samples of air, water, plants, and animals are taken and their α, β and γ activity measured. Human excretions can be sampled and tissues can also be sampled post-mortem. Liquid scintillation counting is very sensitive for β-activity and some discrimination can be made on the basis of energy, e.g. between ^3H or gross β-activity. Suitable samples can be measured for α and γ activity with high energy resolution providing a useful means for identification of the radioactivity. A whole body counter provides the most direct

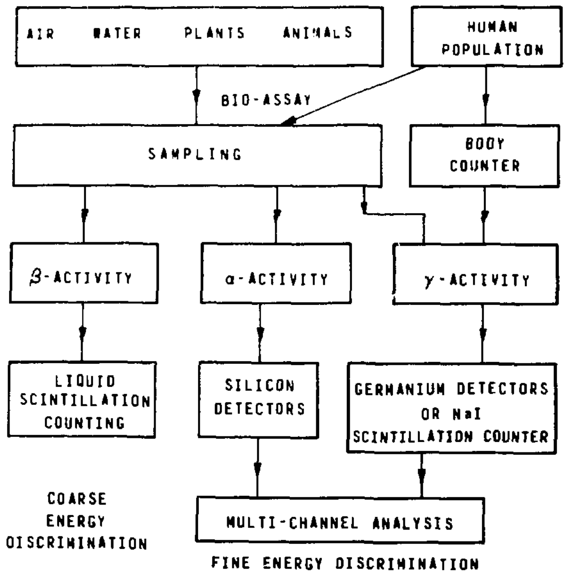


FIGURE 10. ENVIRONMENTAL RADIOACTIVITY MONITORING

monitoring technique and again energy discrimination allows distinction between, for example, terrestial radioactivity and fission products. Discrimination between fission products from one nuclear facility and another more distant one and fall-out from weapons tests may be more difficult.

Environmental doses are measured with dosimeters (usually passive) and dose rate meters. Passive dosimeters are in themselves simple and relatively cheap but require a single complex and expensive reader which, however, may be already available for personal dosimetry within the nuclear facility. For this reason they lend themselves to the widespread use which is needed to monitor the environment in a convincing manner. Unfortunately, it is almost impossible to interpret the doses in terms of their origin. If the environmental dose limits are lower than natural fluctuations in the background dose simple dosimeters cannot be used to decide whether the limits have been exceeded and for this reason electronic instruments which provide information about the energy or time distribution of the doses are needed. However, cost may rule out their widespread use. For this reason the two approaches are complementary.

Some thermoluminescent dosimeters (TLD's) are suited to environmental dosimetry. For this purpose they must have adequate sensitivity to measure the small doses of interest(1 - 100 mrad

(10 - 1000 μGy), depending upon the exposure period). They must have acceptably low fading during the exposure period, bearing in mind the ambient temperature. Tissue equivalence is also desirable. Adequate packaging is required to shield them from light, rain and solar heating. The TLD's and their packaging must be low in radioactivity. The following table lists 5 TLD's which have been used for environmental γ-Dosimetry.

Comparison of Environmental TLD's

Type	Sensitivity Relative to TLD-100	% Fading/month	Tissue Equivalence
CaF_2:Mn	10	∿ 10*	No
CaF_2:Dy	30	∿ 12*	No
$CaSO_4$:Mn	70	∿ 50 (per day)*	No
$CaSO_4$:Dy	20	∿ 2*	No
LiF:Mn (Sensitized TLD-100)	4	< 1 (9)	Approximate

* Manufacturer's Data (Harshaw Chemical Co.)

The table shows some characteristics of 5 sensitive TLD's to permit comparison from the viewpoint of environmental monitoring. The most sensitive, $CaSO_4$:Mn, has a very high fading rate. Therefore, it can be used only for short exposure times but doses as low as 5 μrad (.05 μGy) have been measured (8). CaF_2:Mn and CaF_2:Dy are sensitive and can be used for exposure periods up to one month without large errors due to fading. $CaSO_4$:Dy, also sensitive, can be used up to 6 months. All of these dosimeters suffer from energy dependence because of their high atomic numbers. This can be corrected to some extent by using filters to absorb low energy photons. However, care is needed in selecting filter materials with low radioactivity.

LiF:Mn does not suffer from this drawback. If presensitized with a γ- irradiation dose it is sufficiently sensitive to measure background γ-doses over a three-month period (9). The fading is low enough to use it for a one-year exposure. In environmental monitoring a good deal of the cost is in installing and exchanging dosimeters. For this reason and because seasonal variations are of interest, three months is a suitable exposure period.

Environmental γ-Dose Rate Monitoring

Detector Type	Discrimination possible on basis of Time	Energy
Pressurized Ion Chambers GM Counters	Yes	No
Silicon Detectors Germanium Detectors Scintillators	Yes	Yes

The table shows some detectors which have been used for Environmental γ-Dose Rate Meters and their capabilities to make distinctions concerning the origin of the dose in terms of time or energy discrimination.

In the first group are pressurized ion chambers[10] and Geiger-Müller counters[11]. Pressurized ion chambers are relatively expensive but they are capable of stable and accurate measurements over a long period. For γ-ray energies of interest in environmental dosimetry their sensitivity is approximately independent of energy. Instruments using GM counters can be built at lower cost and are also stable and sensitive but they require correction for energy dependence. Also the radioactivity in their construction materials complicates the problem of measuring low dose-rates.

The remaining three detectors can provide discrimination on the basis of energy as well as time. Silicon detectors are stable and require little cooling to obtain good energy resolution. Germanium detectors have a higher atomic number and have more sensitivity in the photopeak but they require cooling with liquid nitrogen, at least while operating. Scintillators, while available in large sizes, have poorer resolution and stability. To avoid the dependence on temperature, they require some form of temperature compensation when used out of doors.

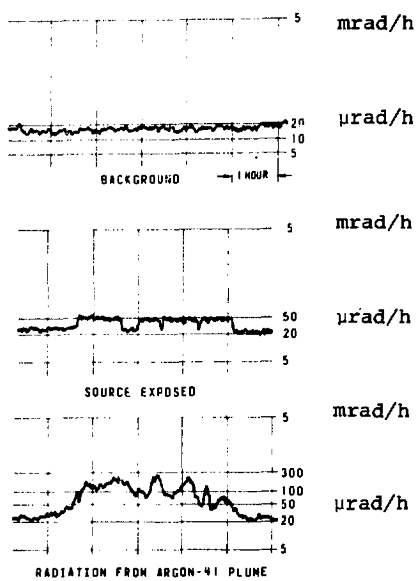


FIGURE 11. TIME DEPENDENCE OF NATURAL AND MAN-MADE DOSE-RATES

1 rad = 10 mGy

The use of time dependence of dose rate can be explained with reference to Figure 11. The top trace shows the dose rate output of an environmental monitor which fluctuates over a small range 15 - 20 μrad/h (.15 - .2 μGy/h) and these fluctuations are *statistical in origin, a GM counter being used as a detector.* The middle trace shows the effect on the background of exposing a large ^{60}Co source in a nearby building. The increase from 20 to 50 μrad/h (.2 -.5 μGy/h) is small but noticeable and introduces no further fluctuation. The lower trace was recorded when the wind was blowing an ^{41}Ar plume from a nearby reactor towards the monitor. In this case the average increase is greater and the noticeable increase in fluctuation is caused by changes in wind velocity. In the middle trace the integrated increase in dose is about 90 μrad (0.9 μGy) and in the lower trace about 300 μrad (3 μGy). Either increase would be easily detectable over a natural annual background of 100 mrad (1 mGy), even if it occurred only once.

However, time dependence would not distinguish between natural *and man-made dose if the man-made contribution was small and did* not vary with time. In this case energy analysis would permit the separation of the two components assuming different photon energies for the nuclides responsible for the dose.

Figure 12, based on data gathered by Gold et al[12], shows the energy spectrum of photons from environmental radioactivity. The spectrum was derived by unfolding the Compton electron spectrum of a cooled silicon detector. The spectrum is not resolved into

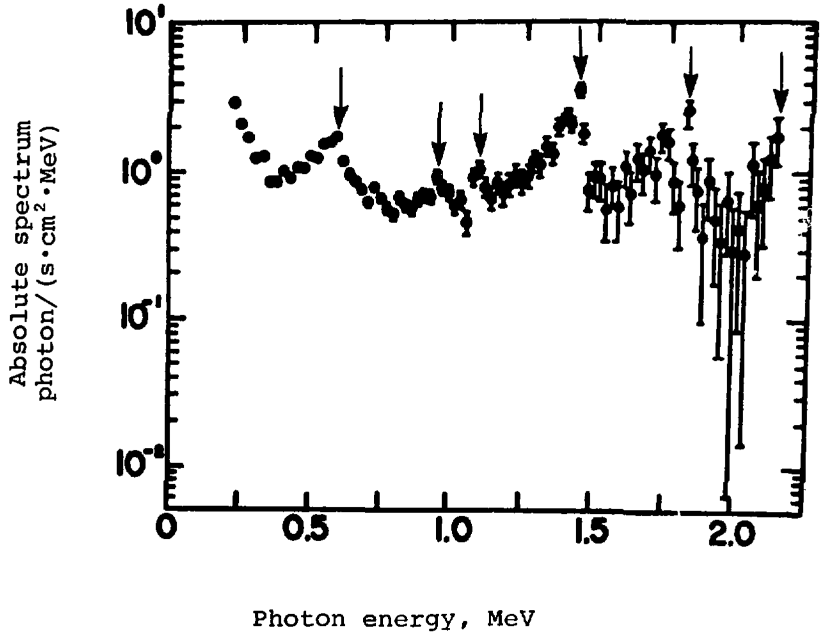


FIGURE 12. ENERGY DISTRIBUTION OF ENVIRONMENTAL γ-RAYS

narrow energy bands because of energy degradation caused by Compton scattering. For this reason a high energy resolution is not needed. However, a small increase in dose would be quite easily seen if the spectral distribution was different from that shown in the figure.

All the instruments and techniques referred to are designed to help in the assessment of dose to humans within a nuclear facility or in its environment. The end use of this assessment is to minimize this dose.

For this purpose the instrumentation must provide data which is significant, unambiguous and reliable. Bearing in mind the large uncertainties in assessment of dose, to which I have referred, great accuracy in dose measurement is not feasible. In fact it is more important to be reasonably accurate always than to be very accurate some of the time and seriously in error at others. Accuracy of measurement is needed to assure reliable monitoring and build confidence in the monitors.

Choices of technique and instrument must be made in the light of circumstances prevailing in each of your countries. This means taking account of your own present and projected radiation protection standards and of the technical facilities available to maintain a reliable monitoring program.

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