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Guidance on the Choice, Use and Maintenance of Hand-held Radiation Monitoring Equipment

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Abstract

This report is designed to assist users to choose appropriate radiation monitoring equipment. It covers a wide range of radiation sources and both dose rate and contamination monitoring. It also includes guidance on surveying techniques, instrument maintenance and ways of determining the nature of potentially complicated radiation fields.

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1 Introduction

It is the duty of an employer to provide suitable instruments for the monitoring of controlled and supervised areas. Selection of suitable instruments can be an easy task in some circumstances but a difficult task in others. It requires a detailed knowledge of the circumstances of potential radiation exposure. There is an obvious subdivision into circumstances where the aim is to limit an individual's exposure to sources which present an external dose rate hazard and circumstances where contamination is present which could be inhaled, ingested or lead to skin contamination.

Dose rate hazards can be generated by radionuclide sources, producing x, gamma, beta and neutron radiation, or by machines such as x-ray sets and accelerators, which produce x and neutron radiation. Radiation can be generated in one form with a particular energy spectrum but can escape from a shielded enclosure either with large changes in spectrum or in a different form altogether. A good example of the first is a well-shielded x-ray enclosure, where the lower energies are virtually completely removed, and only a small fraction of the highest energies escape. As an example of the second case, beta radiation is relatively easy to shield but, in attenuating the beta radiation, a very small fraction of the energy is converted into x-radiation, which is inherently more penetrating. It is this x-radiation which is generally found outside the shielding.

Contamination hazards are generally found where unsealed sources of radionuclides are employed. A fraction can escape to form an airborne hazard or it may be directly deposited on to equipment, buildings and people in the area. The contaminants may be alpha, beta, x or gamma emitters.

It is not always easy to predict which radiations may be present in occupied areas. The circumstances under which monitoring takes place can also have their impact. A hard working environment can demand a particularly robust instrument and this need for robustness can restrict an instrument's radiation performance. The needs of the immediate user should also be recognised. For occasional use by an unskilled person then simplicity is important. For regular use by a skilled person then additional features can produce better quality data.

This report aims to shed light on these problems and help in making an informed choice of instrument.

2 Instrument choice

Instrument choice is basically a process of choosing an instrument which is appropriate to the particular situation in the workplace.

An instrument has to:

(a) be appropriate for the type(s) and energy or energies of the radiations which it is intended to measure,

(b) reasonably unresponsive to other radiations which may be present, such as cosmic and natural gamma background radiation and which might conceal significant levels of the radiations of interest,

(c) measure the right quantity, such as ambient dose equivalent rate for a gamma monitor,

(d) have sufficient sensitivity so that meaningful measurements can be made at the lowest level of interest,

(e) be acceptable to the user, in terms of size, weight, shape, control functions and display,

(f) be sufficiently robust for day to day use,

(g) be maintainable, repairable, inexpensive to live with and have an acceptable useful life.

Examples of particular circumstances and given in Appendix A and there is detailed discussion of the merits and problems of particular instrument types in Appendix C.

3 General approach to surveys

The main purpose of a survey is to confirm that radiation levels are acceptable, in the sense that the designation of the area and the precautions employed in the area remain appropriate. The secondary purpose is generally to check whether levels are increasing at a rate which is likely to require a change in work practices in the area. This can then trigger an investigation into the causes of the increase and a search for ways to halt and possibly reverse the increase.

The information from a survey is of interest to, amongst others, the Radiation Protection Adviser (RPA), the employer and any regulatory bodies. It may well also be of direct interest to the people working in the area who, in a well-run organisation, will be seeking to minimise their doses for a particular set of work practices.

Surveying techniques are very dependent on the radiation sources encountered. Examples are given in Appendix A for a range of circumstances.

Sometimes there may be little information on the source to be surveyed. Appendix B gives guidance on ways of determining the radiation types and estimating the energies present.

4 Care

All instruments require reasonable care in use. All instruments have strengths and weaknesses. General points are listed below.

(a) Avoid temperature extremes and very rapid changes. Do not leave instruments on the back window shelf of a car in the full sun. Temperatures can reach levels well in excess of component ratings. Do not leave instruments in the boot of a car overnight in winter. Taking a very cold instrument into a warm area can result in condensation producing electronic failure. Ion chambers are particularly susceptible.

(b) Make sure that batteries are in good condition. Even modern batteries can leak, particularly when discharged. Remove batteries when an instrument is not to be used for a few weeks.

(c) Buy a good, well-fitting case for the instrument. Much of the damage to instruments is during transport, not during use.

(d) Do not swing probes by cables. This can lead to connector damage at minimum and destruction of the probe at worst.

(e) Keep instruments clean and repair minor damage such as loose screws and missing feet as soon as possible. Check, particularly, battery contacts.

(f) Try to keep to one battery manufacturer, particularly for instruments which have flat spring battery connectors. These tend to deform with use. Batteries vary in length by up to 2 mm. If a long battery is fitted the connectors can deform permanently. If a shorter battery is fitted subsequently then contact will be poor.

(g) Be cautious when using rechargeable batteries. These maintain their output right up to moment of failure, unlike conventional batteries which fade away slowly and predictably.

(h) If an instrument indicates an unexpectedly high dose rate, believe it and leave the area as soon as possible. Do not assume that it is an instrument failure.

5 Maintenance

It is important that instruments are maintained in good working order and that potential problems are recognised early and appropriate steps taken to correct the potential failure.

Radiation protection instruments are relatively simple and easy to maintain in comparison with many other pieces of equipment. The facilities required are simple and will normally be available in any workshop.

5.1 General maintenance

The most important item of general maintenance is looking after the battery box. Changing batteries can damage the battery connectors. Check that the connectors still have enough bite to produce good electrical contact even when the instrument is held at unusual angles. Check that the level of wear is acceptable and that corrosion is not producing poor contract. On instruments that use PP3 style batteries check that the wires from the battery connector are undamaged.

One unexpected aspect is that battery lengths vary considerably within one type. The specification for the common AA cell allows a total variation in length of 2 mm. This means that a change in manufacturer can lead to a change in length. Fitting a shorter battery will produce unreliable contact. Fitting a larger battery will produce a good contact but will often permanently distort the flat spring connectors, leading to poor function when one of the original, shorter, batteries is fitted.

Maintenance otherwise is generally a matter of keeping nuts and bolts reasonably tight and checking for obvious physical damage which would indicate the instrument has been dropped perhaps. If such damage is found then it may well be worth performing a radiation function check.

5.2 Instruments with probes on cables

One of the most vulnerable components is the cable connecting probe and ratemeter, particularly if it is fitted with connectors. Connecting and disconnecting cables will ultimately lead to the connectors coming loose on the cable, perhaps breaking either the centre wire or the braiding or both. Users may be careless about unscrewing collars and may turn the whole connector body. This can twist the connector on the cable leading to rapid failure. Users may also swing the probe by the connector. The connectors and cables are rarely designed for this. Particularly vulnerable in such circumstances are right-angle connectors, where dangling the probe on the cable rapidly leads to failure. Unfortunately most cables with connectors are really rather feeble for industrial use. Cables which are fed through a gland into the probe are generally much more reliable.

Other cable damage includes cuts where the cable has been dragged over a sharp edge or squashed areas where the cable has been trapped by the lid when the instrument was placed in its carrying case.

It is important that cables are inspected regularly.

5.3 Detector windows

Many contamination probes and instruments have thin windows. These are always vulnerable to damage. The effect is obvious in Geiger Müller (GM) tubes, where damage to the window produces instant catastrophic failure. Damage to alpha and beta scintillation probes will produce a light leak, leading to a high erratic background or, in some old alpha monitors, to a fail to danger. In this case there is no obvious background but the instrument simply does not respond to radiation. In sealed proportional counters damage produces a loss of function, effectively caused by an increase in energy threshold as oxygen leaks in and counting gas escapes. In refillable ones damage means excessive refilling of the detector with counting gas. For sodium iodide detectors the windows are generally tougher, but damage can lead to light leaks and, more insidiously, a slow deterioration in the scintillator as moisture gets in. Sodium iodide is hygroscopic. The clear crystal rapidly turns to a yellow powder in the presence of moisture. This leads to a general loss of sensitivity, particularly at low energies.

Any instrument with a thin window should be inspected regularly. For conventional alpha and beta scintillation probes many users are prepared to correct pinhole light defects using typists' correcting fluid. This requires skill and a degree of judgement. The process must be confined to a very small fraction of the detector area, certainly no more than 0.5%, and should only be undertaken if both the RPA and the qualified person (see Section 6) are prepared to accept the slight drop in performance.

5.4 Ionisation chamber instruments

Most of these instruments use desiccators to keep the electrometer amplifier dry. These desiccators will require regular drying, particularly if the instrument is used in cold, damp conditions. On many instruments the inside is quite well sealed from the outside world. If the desiccant seems to need frequent drying then it may be that one of the rubber seals has failed, allowing water into the electrometer.

5.5 Gas refillable proportional counters

These are the most maintenance intensive monitors. The counters require regular (daily, four hourly) flushing with fresh gas to remove the oxygen that diffuses in through the thin window. This can be done directly, from a small cylinder, or the instrument may have a built-in reservoir which requires only occasional refilling. In either case it is important that the detector is flushed regularly. If the instrument is abandoned for any length of time then it may well take several flushings to restore its performance. Such instruments are best suited to regular use and are not suitable for emergency kits, for example, where use is intermittent.

6 Legislative requirements for testing

The Ionising Radiations Regulations 1999[1] require that equipment shall:

(a) be properly maintained so that it remains fit for the purpose for which it was intended,

(b) be adequately tested and examined at appropriate intervals. This testing process should take place at least once every year.

The RPA has a role in this process in advising the employer on appropriate means of checking that the instruments are serviceable, including the nature and frequency of routine checks and on their testing and examination.

Periodic examination and testing is to ensure that the monitoring equipment is not damaged, operates as expected and remains suitable for the expected duration of use until it is next thoroughly examined and tested.

In this context an instrument that operates as expected is one with a radiation response which agrees substantially with the expected value derived from type test data and which also agrees with any previous data derived from its test before use and any periodic test data. The Ionising Radiations Metrology Forum has produced guidance on this matter which has been published by the National Physical Laboratory in Good Practice Guide 14 (GPG14)[2].

This process of thorough examination and testing should take place at least every 12 months, although it is recognised that there may be practical difficulties in achieving this in some circumstances. It is the employer’s duty to ensure that any significant faults are repaired and that the instrument is re-tested after repair where the nature of the repair could affect the performance of the instrument.

Testing should be performed under the supervision of a qualified person, defined as a person who has a good knowledge and understanding of current testing standards and any relevant technical guidance, such as GPG14[2]. The qualified person can be an employee of the employer using the instrument or of an instrument manufacturer, supplier or specialist test house. The employer does not have to appoint the qualified person formally in writing but it is important that both employer and qualified person understand their responsibilities.

The RPA should advise on the type, energy and intensity of the radiations which the instruments can be expected to encounter and this advice must be communicated to the qualified person. The qualified person should also ensure that their clients know exactly what sort of examination and calibrations that they have contracted for and also any relevant limitations.

7 Examination and testing process

7.1 Type tests

Any equipment should normally have been subjected to a type test before it is first put into use. This is a demanding and thorough test of its radiation, environmental, electrical and mechanical characteristics which is performed on one or a small number of production standard instruments to make sure that they are functioning acceptably well when compared with the design specification and also to provide data for all subsequent tests. These tests are generally performed on behalf of or by the manufacturer using guidance from the IEC[3]. A useful summary is also available in IPEM Report 69[4].

7.2 Tests before first use

These tests are designed to confirm that the instrument in question has a similar performance to the type test instrument. These are described fully in GPG14[2] but fall broadly into four categories, as follows.

(a) A check on the instrument's linearity over its intended range of use – for an energy compensated GM detector this would comprise exposing the instrument in the calibration orientation to known ambient dose equivalent rates of ^{137}Cs or ^{60}Co gamma radiation over the operating range which could reasonably be anticipated, given its intended use.

(b) Overload performance – this is to confirm that the instrument's performance at very high levels is correct. In many situations the range of dose rates, for example, which the instrument could reasonably encounter exceeds the maximum useful range of the instrument. This could happen if an interlock was to fail or a source fail to retract into its housing. It is important that thought is given to deciding the maximum dose rate which the instrument could encounter as an instrument failure in such circumstances could lead to high doses, direct injury or death. The RPA should advise the employer on this maximum value so that the information can be passed on to the qualified person. A sense of proportion is required and should take into account the relevant working practices. For example, in a gamma irradiation plant used for the sterilisation of medical products, it could be defined as the dose rate in a maze entrance just before a person can see that the sources are exposed. As a minimum, gamma dose rate instruments should be exposed to 10 mSv h^{-1}.

(c) Energy response – an instrument should be checked at, or below, the minimum energy of use for the appropriate radiation type. For example, for conventional energy compensated GM detectors, which have a lower useful x, gamma energy of 50 keV, a check using ^{241}Am gamma radiation (60 keV) is appropriate as a manufacturing defect which leads to a poor response at 50 keV will be obvious when checked at 60 keV and there is no convenient source of 50 keV radiation. For many beta contamination monitors a check using a ^{14}C contamination plaque (E_{max} = 0.16 MeV) is reasonable.

(d) Uniformity of response – this falls into two broad groups. For dose rate monitoring equipment this generally comprises irradiation of the instrument at ±90º to the calibration orientation in the horizontal plane. Often ^{241}Am gamma radiation (60 keV) is used. For contamination monitoring the corresponding test is to measure the response of the monitor to a small area source at a range of positions over the nominal sensitive area of the probe.

The instrument should also be examined to check that it appears to have been assembled and set up correctly. This process does not normally require the measurement of internal line voltages, for example, unless the qualified person has reason to believe that maladjustment of these could corrupt the instrument's performance in a way which would not show up in the normal test before first use. Normally there is no need to open the case provided the qualified person has sufficient confidence in the general build quality expected. However, if, for some reason, the qualified person has doubts on the build quality, perhaps because of a history of failure in service of similar instruments, then it may well be appropriate that the instrument is examined in more detail.

It may also be appropriate to perform other tests on instruments such as checks on temperature stability or on resistance to interference by radar, for example, particularly if the instruments are to be exposed to unusually high levels. Again, problems in operation of similar instruments may well indicate the desirability of a particular test to weed out badly constructed instruments.

If the examination and testing are satisfactory, a report can be prepared and then authorised by the qualified person. The employer is obliged to keep the report or a copy thereof for at least two years.

7.3 Regular periodic tests

A similar process should take place at not more than 12 monthly intervals. The only significant difference between these tests and the tests before first use is that often there is no need to perform the tests on uniformity of response, group (c). However, the instrument will probably now have seen significant use and the importance of inspection will rise. Many aspects have been covered in Section 5 on maintenance, but, in summary, a degree of wear and tear can be expected on components such as battery terminals, switches, cables and detector foils. It is important that these are taken seriously as a failure, complete or partial, is likely to have a much bigger influence on monitoring or monitoring data than a change of 20% in response to gamma dose rate or surface contamination.

In the same way the test and examination should be carried out by, or under the direct supervision of, a qualified person who should also sign the final report.

7.4 Differences between this process of testing and examination from the standard definition of the process of calibration

Calibration can be reasonably accurately defined as the production of a correction factor to allow a better measurement of some quantity. In many circumstances this is not relevant to the practice of radiation protection. Users of x, gamma survey monitors rarely correct an instrument indication because:

(a) the process of radiation protection does not require very high accuracy results,

(b) the radiation field, in terms of its energy and angular distribution, is not known to any degree in many circumstances because of the influence of scatter and hardening by transmission.

In radiation monitor testing the production of a calibration factor is much more intended to confirm that an instrument is working broadly as expected, often at the ±20% or ±30% level.

In summary, the process of testing a radiation protection monitor is closer to the annual MOT test of a car than a typical calibration.

8 Monitoring point choice

Monitoring points should be designed to confirm that the operator of facilities involving radiation is still in control of these facilities and that nothing unexpected is taking place. Controlled and supervised areas have to be correctly delineated, areas of high dose rate within controlled areas identified to help in minimising staff doses and checks made to ensure that shielding is intact. The selection of monitoring points will often follow a comprehensive survey of the facility.

8.1 External radiation

This section is concerned with the uses of sealed radioactive material, x-ray equipment and adventitious x-ray generators such as electron microscopes and electron beam welders.

8.1.1 Source storage

Generally the boundary of a source store or the outside of a source safe is treated as the boundary of the controlled area. It is important that such stores are monitored whenever additional activity is moved in to confirm that the dose rate outside the store or safe continues to be acceptable. Problems can arise if a larger than expected activity is imported, if the shielding of the source container is less effective than estimated or if the sources are moved closer to the boundary.

Monitoring points should be chosen to check on this. For an unshielded source store the door is often the least shielded area, as brick or concrete walls will offer quite good shielding. This can be confirmed when the store is constructed and a monitoring point marked on the door for future reference. It is also important to check regularly on areas of high occupancy, where the source store backs on to a coffee room, office or waiting room, say. If the wall is homogeneous then monitoring at the level of the sources which give the biggest dose rate contribution is recommended. It is important to check whether rearrangement of the sources could cause a problem. This can occur if the most significant source is normally stored in the centre of an area, to minimise dose rate outside the area, but could be moved closer to a wall.

If the source store has added shielding, such as lead on the door, then checks should be made round the door edges to ensure that the shielding has not been distorted.

8.1.2 Radiography rooms

These are normally designed to produce a specified dose rate at the perimeter. When they are built it is important to perform a detailed survey to confirm that the dose rates are acceptable and the area outside is correctly designated. Areas of weakness include ventilation and cable penetrations, doors or maze entrances and roofs. Scatter from objects above a relatively thin roof can produce dose rates that increase for a limited distance away from the wall, which may seem surprising to the surveyor who will normally expect dose rates to be highest close to the wall. This phenomenon is referred to as sky shine. Monitoring of a new facility should confirm that dose rates around the facility are acceptable, demonstrating that the shielding design is correct and that construction is also correct, with no shielding weaknesses caused by the wrong grade of concrete block, for example. It is important, at this stage, to consider the most demanding situations. This is normally with an uncollimated source positioned closest to the least shielded area, such as the maze entrance or the door.

When the facility has been commissioned and monitored then the focus should change to identifying circumstances that could cause changes in dose rate. Source replacement is an obvious candidate. If a source is changed then monitoring should take place at the point where the highest dose rate is expected. Otherwise, monitoring should be designed to check on dose rates at positions of high occupancy, such as source wind out positions, around the door, particularly if it is shielded, and in the maze entrance. Obviously if any cracks appear in the walls then monitoring should be performed to check that shielding is still adequate.

8.1.3 Confirming that a source has returned correctly to its container

Industrial radiography often uses sources which are wound out to make the radiograph and then wound back into a shielded container. It is essential to check that sources have genuinely wound back into their container and have not become detached. The main problem with this is that many containers use depleted uranium shielding which is mildly gamma active, and the difference in dose rate on the container surface between source present and absent may not be dramatic. Hence it is important to check at a defined point on the container to confirm that the source is present. It is also worth confirming that the source is not trapped at the entrance to the container rather than fully retracted. If there is the slightest doubt then a quick scan along the exposure tube and in the area of the radiograph will confirm that the source has, or has not, been wound back correctly.

8.1.4 Open shop radiography

For open shop radiography the dose rates at defined distances from the source or x-ray tube should be known. Hence the barrier distances also should be well established. It is important to confirm that the barriers have been set correctly by monitoring along the edge of the barrier. Where collimated sources are used, the most important direction is along the main beam, except where it is directed into the ground.

8.1.5 High dose rate facilities

High dose rate facilities such as radiation sterilisation plants have to be treated with caution. Normally installed monitors will be provided, connected to interlocks. These facilities can be treated in a similar way to normal industrial radiography facilities but account should be taken of the very high dose rates which could be encountered in the event of failure, such as a drop in water level in a source storage pond or a failure to house the sources correctly.

8.1.6 Adventitious x-ray generators

These include electron microscopes, electron beam welders and high voltage vacuum tubes, such as in radar equipment. The dose rates from such devices tend to be low, but they tend to be quite complicated in shape and potential high dose rate areas are difficult to predict. Monitoring of new equipment should concentrate on areas such as joins in shielding and cable penetrations. Monitoring after repair or servicing should concentrate on areas where shielding may have been distorted, incorrectly installed or missed out completely.

8.1.7 Crystallography equipment

Crystallography and similar equipment uses very narrow, high intensity, low energy x-ray beams. Monitoring should concentrate on areas such as joins in shielding between beam tube and attachment. It should be noted that the radiation energy present is often defined by the tube target material, rather than by the potential on the tube.

8.1.8 Chemical processing equipment

This covers a range of situations, from natural activity in mineral processing to uranium fuel reprocessing plants. Often activity will accumulate in specific areas, either by design in filters or by accident in valve bodies and pipe bends. The accidental ones are more difficult, but operational experience should indicate to the operators where the dose rates tend to be highest and regular monitoring should be performed to confirm that they are acceptable. Sometimes activity which has built up in one area can be rapidly stripped off to appear somewhere else. Hence a drop in dose rate in one area may well have caused an increase in another.

8.2 Radioactive contamination

Monitoring of surface contamination is important where unsealed radioactive material is being processed or handled.

8.2.1 Radiopharmaceutical laboratories and similar research facilities

Handling of radioactive materials is generally performed for small quantities on open benches, for larger quantities in fume cupboards and for the largest quantities in glove boxes.

Frequent contamination monitoring will be required in the area where the source is being handled, to check for splashes and drips. Other areas, such as the edges of benches, the wall behind benches and the floor immediately in front of the work area should also be checked. Areas round sinks used for the disposal of radioactive material should also be checked regularly and other sinks checked at less frequent intervals.

Glassware, tools and other equipment should also be monitored as should the hands and clothing of the workers. It is also good practice to monitor things that are frequently touched such as door handles, taps and light switches to check that someone with poor technique is not contaminating the area.

In the event that a large area of contamination is found then surveys of the laboratory, particularly the floor, and other areas used by the workers should be performed.

For high levels of activity glove boxes are employed. Contamination monitoring should be performed regularly on the inside of the gloves, to confirm integrity, particularly at the hand end and around the seal between glove and box. Posting in and out areas should also be checked.

When maintenance is undertaken, monitoring of any ventilation ductwork is essential. Monitoring is also important when working on normally inaccessible areas such as on roof beams where undisturbed, low level deposition can occur over long periods. This is particularly important when working in older buildings where historical deposition may exist, dating back to periods during which control of airborne activity was less rigorous.

8.2.2 Source packing and unpacking areas

Any area where sources, sealed or unsealed, are handled has the potential for contamination. Such areas should be monitored regularly, perhaps after certain types of package are handled or after a particular level of activity has been handled.

Monitoring should concentrate on areas where a leaking or externally contaminated source could have deposited activity. Anything used to handle the sources such as tongs, reaches or remote manipulators should have the areas which contact the sources checked, as should any trays or containers used in the manipulation of sources.

8.2.3 Nominally inactive objects being passed out of active areas

Objects which are leaving active areas should be monitored carefully, either directly, where the radiations are reasonably penetrating and the surfaces easy to access, or by wipe, for lower energy nuclides and complicated shapes.

Electronic equipment fitted with cooling fans constitutes a particular problem in such areas as activity may be drawn into the equipment.

9 Instrument selection

1 Determine the radiation types, energies and intensities which the instrument will be expected to measure.

2 Determine the quantity or quantities which the instrument will be expected to measure. For example, for the measurement of gamma dose rate the usual quantity is ambient dose equivalent rate. For surface contamination the desired endpoint is Bq cm^{-2}, but the normal instrument indication is in counts per second.

3 Is there a possibility of any interfering radiations, such as high levels of gamma dose rate when the main aim is to measure alpha surface contamination? If so, these will have to be quantified so that instrument specifications can be checked to ensure that the instruments should work and also so that appropriate tests before use can be selected.

4 Is the instrument to be used in a tough environment? Is it likely to be knocked and dropped? Does it need to be waterproof or at least well sealed? Are there any limitations such as use in an explosive atmosphere? What temperature range is expected?

5 What will the end user expect from the instrument? What sort of weight will be acceptable? Will the instrument have to be carried up ladders? Does it require a light so the reading can be seen in poor light? Which geometry is best? Sometimes, for gamma dose rate monitoring, users prefer a display on the opposite face of the instrument to the detector. Then the instrument can be held at arm's length and the display read conveniently. For more restricted areas a display on the top and a detector on the front face of the instrument allows the user to hold the instrument close to the body and look down on it.

There is a very broad choice between analogue and digital displays, with users expressing strong preferences. Establish these, but also remember that digital displays are increasing in quality rapidly and many users previously committed to conventional analogue meters are now quite happy with liquid crystal digital displays.

6 Is there a preference for battery type or types? Are certain types unacceptable? What minimum battery life is required? Remember that a longer battery life generally means a heavier, bulkier battery and a heavier, bulkier instrument.

7 Some instruments offer data logging capability. Would this be an advantage for the application under consideration? Such a facility will generally add a small cost to the instrument but could add a large preparation cost, if bar codes or micro cans have to be placed around the site, and also a large cost for the software to make good use of the data.

8 Are smart instruments a good idea, ie instruments where a ratemeter can be plugged into any of a series of probes without adjustment being required? Or would it make more sense to have permanent probe and ratemeter combinations, which generally allow a cheaper ratemeter?

9 How clever should the instrument be? For a contamination monitor is there any advantage in having a set of calibration factors stored for a range of nuclides or would a simple counts per second display be less prone to misinterpretation?

10 Records

Records of monitoring should be kept for at least two years. It is important that data for a particular monitoring point can be accessed quickly and easily. There is a variety of means which can be employed, depending on the number of monitoring points to be covered and the complexity of the situation.

The aim should be to cover:

Where

- the location of the monitoring points, described clearly and unambiguously.

When

- when the monitoring took place.

Who

- who performed the measurements.

With what

- which piece of monitoring equipment was used and the date of test of the equipment.

How

- how that piece of equipment was employed – this could be a reference to a written procedure, for example.

How much

- the measured value of the dose rate or contamination level.

  It is important in many situations not to log the result as zero. For beta contamination surveys it is important that the surveyor's best estimate of the count rate is recorded. This can then be compared with the relevant background value and with the appropriate limiting value. Similarly, for alpha surveys, <0.2 count per second is better than zero as is $<X\ \mu\text{Sv h}^{-1}$ for dose rate surveys, where X depends on the instrument sensitivity. This approach will provide a convincing picture of radiation levels in a particular area to the RPA, the employer and any inspecting agency.

In simple situations data can be stored on paper very conveniently. There are two main approaches. One is to record the results from one point on a particular page, the other is to have a page for each phase of monitoring. The first method is useful in identifying trends while the second can be filled in more easily as monitoring takes place. A variation on the first approach would be to graph the results. Using the date as one axis will give a very clear indication of any trend with time.

For more complicated situations a computer database is ideal. It is perfectly practicable to transcribe monitoring results from a hand written sheet into the database but this can be a time consuming, boring process and errors can result. Instruments which log value and position are increasingly available and these have the advantage that the data can be directly downloaded. They also have the advantage of credibility, in that the presence of a value in the database makes it very likely that the measurement was actually made, whereas hand entered data can be made up or copied from previous results.

As in all computer data management it is essential that data are backed up in some way, either electronically or, if derived from hand written sheets, by storing the original sheets.

11 Training for users

Users should be trained to use instruments effectively to generate good quality monitoring data efficiently and safely. Staff maintaining and testing equipment should be trained to discharge their duties efficiently and safely.

Users should be given an understanding of:

Why

- An explanation of why radiation is seen as a hazard.
- The legal obligations of the employer and employees.

What

- The characteristics of the radiation types which are likely to be encountered.

With what

- A description of the types of monitoring equipment provided, which type to use for which monitoring situation and the limitations of each type.

Checking

- Does it have a valid test certificate?
- Does it look as if it is in working order? Is there, for example, obvious damage to cable or connectors?
- Is the battery good enough to last out the work period? For conventional instruments the needle should be well within the acceptable battery condition range and not visibly moving.
- Is the background count rate believable? If it is a scintillation monitor does it respond when held close to a fluorescent or other bright light? A change in count rate, up or down, shows the presence of a light leak. Does the count rate change when the cable between probe and ratemeter is flexed?
- Use of check sources – if these are available, and they can be extremely useful, how should they be employed?
- What to do if the instrument appears faulty. A user should know who to refer to, where to put the instrument and how it should be labelled. There should be no excuse for someone putting the instrument back on the shelf and taking the one next to it.

Where

- Where each monitoring point or area is and how to identify it.

When

- The frequency that monitoring should take place. This could be task based, eg after a filter change or flask movement, or time based, once a day, week, month or quarter.

How

- The process of making the measurement. This should cover:

(a) the reference direction, ie the direction of radiation incidence for which the manufacturer designed the instrument,

(b) how to turn on the instrument including battery checking and range selection,

(c) use of any audio output (clicker or alarm) – the audio output gives an instant indication of the count rate rather than the damped or average value indicated on the display,

(d) for contamination monitoring, the correct distance between probe and surface and how to maintain it safely,

(e) how to take the measurement, in the sense of a length of time to wait and how long to average the indication for – this should also cover the interpretation of logarithmic scales,

(f) where and how to record the data,

(g) how to respond to any unusual values,

Excessively high results point to shielding failure, hot particles or excessive contamination. It is important that such results are reported quickly to someone who can deal with them. Low values could also indicate a missing source, which should also be reported quickly, or a possible instrument failure. For very high levels it is important that the individual moves away quickly and does not assume it is an instrument problem.

(h) the environment causing instrument problems,

High electromagnetic, electrostatic and magnetic fields can cause high count rates or fail to danger. Very bright lights can cause spurious count rates. Taking cold instruments into warm, damp environments can cause condensation, giving spurious high dose rates on ionisation chamber instruments.

(i) failure modes for the instrument,

For scintillation based contamination monitors this could cover light leaks. Probe and ratemeter combinations often suffer from cable damage. Touching the windows of thin end window GM detectors with anything sharp generally results in implosion. Regular battery checks are essential.

(j) maintenance by the user – this could include zero setting, battery changing, cleaning and checking.

How not to

- Things not to do. The classic temptation is to swing probes by the cable. Unfortunately the standard UK Pet-Pet cable is not up to this. Other common faults include putting thin window detectors down on sharp things, such as nail ends and swarf, letting instruments become damp and not drying them and throwing instruments into the backs of cars, not in a proper box.

Personal safety

- The person performing the monitoring should be safe. Generally training should cover conventional safety and radiological safety. Particular emphasis should be given to dose avoidance, particularly in high dose rate plants. This would include the classic time, distance and shielding, with particular emphasis on instrument choice and use. For example, a telescopic monitor can be useful in some circumstances. Very clear limits on permissible dose rates should be established to avoid over-enthusiastic staff investigating high dose rate areas. Avoidance of personal contamination is a priority.

This list may seem intimidating but the training should fit the circumstances. If an individual has to deal with one relatively low activity beta thickness gauge source using one instrument then the training programme would be very short. Training for plants reprocessing irradiated fuel, however, would have to be much more comprehensive.

12 Training for maintenance staff

The maintenance of radiation monitoring equipment is essential for good quality results. Section 5 covered typical maintenance procedures. Manufacturers' manuals are the first source to be consulted. These will usually provide all the information necessary for routine maintenance and, sometimes, for simple repairs and adjustments.

Staff undertaking maintenance should be capable of making repairs and adjustments up to a specified level. Many users will only undertake routine maintenance and will send any instrument requiring repair or adjustment to a repair house or back to the manufacturer. A normal level of manual dexterity will be all that is required. Other users, with more instruments, may wish to perform repairs themselves, in order to avoid the inevitable delays caused by sending instruments away. In this case a much higher level of knowledge will be required. Typical qualifications include City and Guilds, ONC, HNC or higher qualifications in electronics.

Differences from many forms of electronic maintenance include:

(a) the presence of high voltages, up to 2.5 kV, on proportional counters, scintillation detectors and some neutron dose rate monitors,

(b) the need to use radiation sources for setting up and testing,

(c) the need for a very high level of cleanliness when working with ionisation chambers,

(d) the importance of not making modifications to detectors or their mountings.

Using conductive silver based paint instead of graphite inside an ionisation chamber will raise the instrument's low x-ray energy response.

Holding a GM detector in with a spring steel clip instead of a nylon tie will reduce the low energy photon response. Extending the length of cable between probe and ratemeter can change the low energy threshold of scintillation and proportional counters. This is unlike most radiofrequency work where extending a cable with appropriate connectors and cable produces little effect.

Using the wrong thickness or material for ion chamber windows can change the beta response, particularly, dramatically.

The windows on end window GM detectors are particularly vulnerable. Particular care is required when changing detectors.

It is important that instruments from contamination areas are looked at suspiciously. Accessible areas of an instrument can be completely clean but areas which are accessible only during maintenance can become contaminated.

In GM based equipment which operates up to very high dead times, care is vital when changing detectors. Using different anode clips, anode resistors or anode resistor lead lengths can change the response to high dose rates drastically.

Fitting new windows to scintillation detectors requires care to ensure that there are no light leaks.

Rewiring proportional counter detectors is demanding as the wire is only 25 to 50 μm in diameter.

The list above is not exhaustive but it covers the more unusual aspects of repair. Hence staff tend to require both a general knowledge of equipment maintenance and a particular knowledge of radiation monitoring equipment.

13 Acknowledgements

This work was supported by the Health and Safety Executive. The author is also grateful for the advice of his colleagues at NRPB and of radiation users generally. He particularly acknowledges the contributions of Mr Gordon Batty, ex Windscale, Dounreay and NRPB, now retired, and Mr Danny Blundell, ex NRPB and Heysham 2 Power Station.

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APPENDIX A
Exposure Situations and the Equipment and Techniques for Monitoring Radiation Levels

A1 Industrial radiography using energetic gamma emitters

For normal industrial radiography of welds in steel pipes and ferrous forgings and castings the most common nuclide is ^{192}Ir. There are others but all emit gamma radiation with energies of a few hundred keV up to 1.25 MeV. The main emissions from ^{192}Ir are given below.

Gamma emissions *E* (keV)	Fraction (%)
296	14
308	14
317	40
468	23
589	2
604	4
613	3

The shielding produced by the casting under examination, any exposure collimator and any additional shielding will tend to harden the radiation, removing the lower energy components preferentially.

Multiple scatter from the walls of a shielded enclosure out through a maze entrance will tend to soften the beam, ie reduce its energy. However, a significant component below 60 keV is unlikely.

Suitable instruments

- Conventional energy compensated GM detector.
- Thin window energy compensated GM detectors.
- Ionisation chambers.
- Scintillation based dose rate monitors.

Generally the best

- Conventional energy compensated GM detectors.

Survey procedure

(a) Confirm the instrument has a valid test certificate.

(b) Perform a function check on the instrument, confirming that the battery condition is adequate and is showing no signs of fading, that the background count rate seems believable and that the instrument seems generally in good order.

(c) If a check source is available, confirm that the instrument is giving the correct reading.

(d) For enclosure radiography, where the source is in a shielded room, monitor areas of potential weakness where shielding may have become damaged or may have been removed. The edges of doors and any penetrations through the shielding should be checked carefully. Note that where the roof of the enclosure is relatively thin then the maximum dose rate may be away from the walls of the enclosure. This can be the case where there is a crane rail running above a removable roof, which can generate scatter.

(e) For open shop radiography confirm that dose rates at and outside the barriers are acceptable.

(f) Use any audio output. This gives an instant indication of dose rate, rather than the damped one provided by the display. If the click rate increases, pause for a few seconds to allow the instrument reading to stabilise.

(g) Take an eye average of the indication. Do not record the peaks. Particularly at low count rates the indication can fluctuate by tens of per cent.

(h) Remember that an instrument indication can take up to ten seconds to stabilise. Have patience. The more sensitive the instrument, the lower the level of fluctuation and the less time that the operator has to wait to allow the indication to stabilise.

A2 Industrial radiography using very high energy x-rays (>1 MeV)

Generally the radiation source is a betatron, which produces a very high energy pulsed electron beam which is directed on to a target, generating x-radiation. The advantage of these units is that they can generate a very high energy beam without using a high energy, high activity source such as ^{60}Co. The two important aspects of this type of source are the very high energy, typically about 6 MeV, and the pulsed nature, typically a 200 Hz beam with each pulse being a few microseconds long.

Suitable instruments

- Conventional energy compensated GM detectors.
- Thin window energy compensated GM detectors.
- Ionisation chambers.
- Scintillation based dose rate monitors.

Generally the best

Probably ionisation chamber instruments.

GM detectors have a count rate limitation when used with pulsed sources. For pulsed sources producing narrow (up to tens of microsecond) pulses it is important that the count rate from the detector does not exceed 30% of the pulse repetition frequency, otherwise the instrument will under-read. Hence it is essential to know the sensitivity of the instrument [in counts $s^{-1}/(\mu Sv\ h^{-1})$] and to identify a maximum trustworthy count rate. This leads to the unfortunate circumstances that the higher the sensitivity, the lower the maximum useful indication.

GM detectors will give a completely false reading at high dose rates, for example close to the target in the main beam. At the ultimate the detector will record one pulse per radiation pulse. For a 400 Hz machine this means a maximum count rate of 400 s^{-1}. If a relatively high sensitivity detector is used, for example one giving 5 $s^{-1}/(\mu Sv\ h^{-1})$, then that gives an ultimate indication, at no matter how intense a dose rate, of 80 $\mu Sv\ h^{-1}$.

However, GM based instruments are satisfactory provided the detector sensitivity has been well chosen and provided the maximum believable dose rate has been calculated and the user informed.

Survey procedure

See Section A1.

A3 Industrial radiography using relatively low voltages, and baggage and security x-ray machines

Typically this involves using x-ray sets operating with maximum potentials in the range 50 to 400 kV. The lower potentials are used for quality control of materials such as aluminium, whereas the higher potentials are used for radiographing thin steel fabrications, such as piping.

The radiation characteristics for these sets differ greatly from gamma radiation. Gamma radiation occurs at discreet energies. X-radiation at the output from the x-ray tube has a spectrum which rises from zero at very low energies, peaks in intensity at an energy equivalent to about 30% of the applied kV and then falls to zero at an energy in keV equal to the tube potential in kV.

Hence there is almost always the possibility of a significant low energy component at the output from the x-ray tube. Any form of intact shielding by concrete, lead or steel will preferentially attenuate the low energy end of the spectrum, reducing the dose rate but, at the same time, increasing its average energy. A few mm of steel or lead or a few cm of concrete will remove any component below 50 keV. However, scatter round a door or from a maze will reduce the average energy. Open shop radiography can obviously present the full spectrum at a barrier, particularly if the beam size is larger than the object to be examined.

Suitable instruments

- Conventional energy compensated GM detectors.
- Thin window energy compensated GM detectors.
- Ionisation chambers.
- Scintillation based dose rate monitors.

Generally the best

- Thin window energy compensated GM detectors. Conventional energy compensated GM detectors can be used for the higher kV sets or where shielding has hardened the beam.

Monitoring procedure

For industrial x-radiography equipment follow the suggestions in Section A1.

For baggage x-ray equipment, the highest dose rates occur when a large volume, low atomic number object is passing through the beam. Normally, then, a large polyethylene container filled with water is used as the scattering object and monitoring performed while it is in the beam. The highest dose rates are generally encountered when the vertical fan shaped beam is just buried within the nearer edge of the scattering object.

A4 Flash x-ray sets

Battery powered x-ray sets are popular for security applications such as the radiography of suspect packages. They have very unusual characteristics in that they produce a short but intense pulse of x-radiation at a relatively low potential. The maximum exposure time is typically three seconds. Monitoring of these using conventional ratemeter based equipment is not possible. The only satisfactory method is to use an ionisation chamber instrument with a sensitive dose range. The monitor is placed, the indication zeroed and the x-ray unit triggered. The new indication is then recorded. Dose rates over an hour can be calculated by multiplying the recorded dose by the number of exposures per hour.

A5 Industrial sterilisation units

High dose rate x or gamma radiation is frequently used for the sterilisation of medical supplies and similar applications. The dose rates involved are extremely high, in excess of 100 kGy h^{-1}. Instruments are used in two modes in such plants. One is to confirm that the dose rates on the outside are acceptable, normally less than 7.5 μSv h^{-1}. Instruments used only for such functions are unlikely to encounter extremely high dose rates. Section A1 on industrial radiography using energetic gamma emitters should be consulted for appropriate types. The other application is much more demanding. These are instruments which are to be carried by personnel when entering the irradiation plant. In the vast majority of cases the various controls and interlocks which are designed to ensure that the sources or x-radiation sources are safe will be working correctly. However, there is always an extremely small possibility that there may some form of failure which leaves the source at least partially exposed while allowing access.

It is important that instruments used during entry should behave correctly if they encounter a very high dose rate. This will normally mean going straight to their overload indication. The instruments used for this purpose should have their performance confirmed at the maximum credible dose rate which they could reasonably encounter. This is not the maximum accessible rate if a failure takes place but more the maximum rate which a user could encounter in the entry maze just before he or she can see that the source is exposed or some other failure has taken place. Typically the dose rate will be of the order of 100 Sv h^{-1}.

Suitable instruments

The instrument is used purely as an indicator, not to measure the dose rate. The radiations are also extremely penetrating. For virtually all applications a relatively insensitive conventional energy compensated GM detector instrument will be the most reliable and quickest to react. The instrument should have a logarithmic scale. Range switching or detector autochanging is not acceptable as both may slow down the identification of the presence of very high dose rates.

Testing should confirm that the instrument goes rapidly to overload at the maximum credible dose rate that it could encounter and that it remains off-scale and does not fail to danger. The majority of GM detectors which operate at 400 to 600 V will operate correctly, whereas many which operate at 900 V will fail to danger.

A6 Transport of large gamma emitting sources in shielded containers

Road, rail, ship and air transport large numbers of high activity gamma sources. These sources are generally extremely well shielded. However, on occasion package design has been found to be defective. Monitoring such packages has close parallels with the monitoring performed during industrial radiography using energetic gamma emitters, and generally a conventional energy compensated GM detector of the appropriate sensitivity will be appropriate. If anything, compact size and a high degree of robustness are even more important as monitoring may involve climbing on to vehicles.

A7 Level gauging using gamma emitting sources

These are very popular in industry for the measurement of the level in hoppers, the height of molten steel in a mould and similar applications. The majority of sources used are ^{137}Cs. The source is in a collimated housing on the one side of the volume to be measured with a detector on the other. Section A1 on industrial radiography using energetic gamma emitters gives advice on monitoring instruments and techniques.

A8 Finding lost gamma sources

Occasionally gamma sources are lost or stolen and it becomes necessary to search for them. In such cases the main requirement is a very high sensitivity. Other dosimetric properties such as a good energy response are generally irrelevant. The best instrument for confirming that a source may be present and identifying its general position is a large sodium iodide scintillation detector. Such detectors have a very high sensitivity. For example, a 51 mm diameter, 51 mm deep detector has a sensitivity of approximately 1500 $s^{-1}/(\mu Sv\ h^{-1})$ for ^{137}Cs gamma radiation and a normal background count rate of 50 to 200 s^{-1}. It is easy, using such equipment, to detect sources which produce an increase in count rate of 50% over background, provided the background is reasonably stable. For areas where it is variable, such as in a built up site where building materials will have an influence, then the ability to detect sources will be reduced.

Suitable instruments

- Large sodium or caesium iodide scintillation detector based instruments.
- Large plastic scintillator instruments.

Generally the best

- Where a compact detector is required and where energy information is required, the caesium iodide detector.
- Where toughness is required, the plastic scintillator.

A9 Adventitious x-ray generators

Many pieces of equipment have the potential to generate adventitious x-rays. Any device which employs an electron beam will produce x-rays. Normally these are efficiently shielded but it is important to check that the shielding is functioning correctly. Typical examples include electron beam welders, electron microscopes and very high voltage cathode ray tube devices. In the majority of surveys it is likely that the dose rates are effectively at background. This offers the possibility of checking the equipment with a very high sensitivity instrument, which may well not be marked in μSv h^{-1} but in counts per second and which also has a rapid change in response with radiation energy. Normally the count rate will be at background levels but even if it is slightly elevated then it is possible to estimate the radiation energy and calculate the dose rate using the energy response given in type test data or in the manufacturer's handbook. This dose rate will generally be so far below levels of regulatory concern that the high uncertainty will not be significant.

In the event of a really significant dose rate being found then the optimum solution is not to measure it but to shield it, or correct whatever fault has caused it. If this is not possible then it may be necessary to make a measurement with an instrument with a lower sensitivity but a good energy response to determine whether the levels are acceptable.

Suitable instruments for the initial search process

- Thin windowed, thin crystal sodium iodide detectors.
- Thin end window GM detectors.

Generally the best

- The scintillator instruments generally make the location of defects easier but they may well go off-scale. The end window GM instruments have a much lower sensitivity.

Measurement of dose rates when defects have been located

As indicated previously, in many cases the best option is to shield the radiation. However, in some cases, this may not be possible.

Suitable instruments

- Thin window energy compensated GM detectors.
- Ionisation chambers.
- Scintillation based dose rate monitors.

Generally the best

- Probably the thin end window energy compensated GM detector, provided the user is aware of the likely low count rates which may have to be measured. Versions with the detector on a probe are to be preferred for monitoring complicated equipment.

Summary

Monitoring problems in this area can generally be summarised as detect first, measure later. It will often be quicker and more effective to monitor using a very high sensitivity detector and then measure the high spots rather than scan the object slowly using a less sensitive detector with good dosimetric properties.

A10 Monitoring of x, gamma dose rates from radiopharmaceuticals

Large numbers of packages are transported containing radiopharmaceuticals. Some are x, gamma emitters, some of which, such as ^{125}I, generate low energy but still reasonably penetrating x-radiation, ie 27 to 35 keV. Many are beta emitters. The beta radiation is always completely attenuated but the associated Bremsstrahlung may be relatively penetrating. As a consequence any radiation dose rate monitor must cover a wide x, gamma energy range. This rules out conventional energy compensated GM detectors for general application as these do not respond correctly to radiation energies less than approximately 50 keV.

Suitable instruments

- Thin window energy compensated GM detectors.
- Ionisation chambers.
- Scintillation based dose rate monitors.

Generally the best

- Thin window energy compensated GM detectors.

A11 Thickness gauging equipment using low energy x-ray tubes or low energy x, gamma sources

Thickness gauging of plastics, paper and cardboard is sometimes performed using low energy photon sources, such as x-ray tubes or nuclides such as ^{55}Fe, which emits 5.9 keV x-radiation. The gauge is generally well shielded but inevitably there is a slot where the material to be gauged passes into and out of the unit.

The monitoring problem is similar to that involved in the measurement of adventitious x-radiation and can be tackled in a similar way, ie detecting first and, if an apparently significant radiation field is encountered, measurement later.

Instruments for searching

There are two suitable types of detector, thin sodium iodide detectors and thin end window GM detectors. The sensitivity and low energy response must be adequate for the limiting dose rate and the expected spectrum.

Instruments for the estimation of dose rate

The same instruments can be used provided the radiation mean energy is known and credible type test data are available. If the source is ^{55}Fe then response data are likely to be available for both instrument types. These can be used to convert the indication from counts per second to $\mu Sv\ h^{-1}$, directional dose equivalent. If the source is a low energy x-ray tube then the process is more complicated. The easiest approach is to determine the half-value layer using thin aluminium or plastic absorbers. The half-value thicknesses are tabulated below, derived from Hubbell and Seltzer[1].

The effective energy of the beam can be interpolated from the values tabulated below. In combination with type test data this value can be used to estimate the response to the leakage radiation which is being monitored.

	Half-value layer (mm)	
Energy (keV)	Aluminium	PMMA (Perspex)
5	–	0.24
10	0.10	2.0
15	0.34	6.6
20	0.8	–
30	2.6	–

Other types of instrument are rarely suitable. The energy compensated GM types do not operate well at very low energies, the ion chamber instruments tend to have a very large averaging area and to be too bulky and the plastic scintillator types do not work well at very low energies.

A12 Crystallography x-ray equipment

Crystallography x-ray equipment generally employs a copper or molybdenum target x-ray tube, operated at relatively low tube potentials, up to about 50 kV. The useful parts of the x-ray spectrum generated are the characteristic x-rays, at approximately 8 keV for a copper target and 17 keV for a molybdenum target. Normally, leakage from x-ray equipment is dominated by the high energy end of the possible spectrum. However, for this type of equipment, and particularly for copper, radiation leaking through shielding defects is dominated by the characteristic radiation.

In many ways the monitoring problem is similar to that involved in the measurement of adventitious x-radiation and can be tackled in a similar way, ie detecting first and, if an apparently significant radiation field is encountered, measurement later.

Instruments for searching

There are two suitable types of detector, sodium iodide detectors and thin end window GM detectors. The sensitivity must be satisfactory for use at the two energies of interest, 8 keV and 17 keV.

Instruments for the estimation of dose rate

The same instruments can be used for the estimation of dose rate, provided their sensitivities are known. There is an additional type of instrument which uses a relatively high pressure GM detector provided with an energy compensation filter which has the advantage that it is calibrated directly in dosimetric units. The disadvantage with this type of unit is that its response is highly directional and its angle should be adjusted to maximise the indication and that value recorded.

It should be noted that this type of equipment produces a very intense x-ray beam. It is important that the main beam is properly shielded and that the person performing the monitoring has no access to the main beam.

A13 Environmental gamma dose rates

Frequently there is a requirement to monitor very low x, gamma dose rates at site boundaries, normally to assess public exposure.

Dose rates of interest normally cover from normal background levels (0.03 $\mu Gy\,h^{-1}$ air kerma) to 1 or 2 $\mu Gy\,h^{-1}$. Suitable instrumentation has been discussed in detail in Technical Guidance Note (Monitoring) M5[2], but the requirements are summarised here.

These are:

(a) an adequate sensitivity,

(b) an acceptable energy response over the range 60 keV to 7 MeV,

(c) a reasonably low inherent signal, ie the signal produced by radioactivity incorporated in the instrument.

Suitable instruments

- Large energy compensated GM detector connector to a scaler-timer.
- Large energy compensated proportional counter detector connected to a scaler-timer.
- High pressure ionisation chamber instruments.
- Large volume plastic scintillator instruments.

Generally the best

- The energy compensated GM detector type. For greater sensitivity but still at a low cost three detectors can be connected in parallel to a single scaler-timer.

A14 Beta thickness gauges

Beta radiation sources are commonly found in paper and board manufacture and in the processing of printed circuit boards. The source is selected according to the material to be measured and its thickness. Beta sources with maximum energies between ^{14}C (0.167 MeV) and ^{90}Sr + ^{90}Y (2.2 MeV) can be encountered. Beta radiation is relatively easy to shield but the associated Bremsstrahlung is more penetrating. Bremsstrahlung is the x-radiation generated by beta particles slowing down. Its maximum energy is that of the maximum energy of the beta source. However, in common with x-ray generation, the mean energy of an x-ray is about 30% of the energy of the electron causing it. In addition, beta radiation has an energy distribution between zero and the maximum energy for the nuclide in question, with the average at about 30% of the maximum. The beta radiation also loses energy as it passes into a material. These factors combine to ensure that the Bremsstrahlung spectrum has a much lower energy than would be expected from the maximum energy generated by the nuclide.

If the Bremsstrahlung has to penetrate relatively high atomic number shielding then the lower energy components will be preferentially attenuated producing a less intense spectrum with a higher mean energy.

The radiation spectrum emerging from these machines is thus rather complicated. From the relatively unshielded areas, for example slots where the material to be measured enters and leaves the machine, there will be a mixture of beta radiation which has been scattered, and thus had its energy reduced, and Bremsstrahlung. For the shielded areas the only radiations present will be the relatively penetrating component of the Bremsstrahlung.

Suitable instruments

- Thin end window GM detector.
- Ionisation chamber.

Generally the best

- Thin end window GM detector, despite the uncertainty caused by energy response variations. An appropriate response factor is generally that for ^{137}Cs gamma dose rate. This will normally lead to an overestimate of the Bremsstrahlung component and a slight underestimate of any beta component.

A15 Neutron dose equivalent monitoring

Neutron dose equivalent rates are encountered in a variety of circumstances. Some of these are unique to the nuclear industry, such as neutron dose rates from nuclear reactors, irradiated fuel and the storage of plutonium.

Outside the nuclear industry neutron sources, often ^{241}Am + ^{7}Be, are used in borehole logging, soil moisture content measurement and tarmac quality assessment. Adventitious neutron dose rates are encountered in high energy accelerators, which are designed to produce x-rays for therapy or industrial radiography, but which, at accelerating potentials above approximately 6 MV, can also produce neutrons.

An important difference between high energy neutrons and x, gamma radiation is the very high dose equivalent per neutron striking the body. This is partly because the energy generated per neutron incident on the body is higher because of the high probability of interaction and the energy released in some of the capture reactions. The other reason is the high radiation weighting factor. From the point of view of monitoring this difference is a disadvantage. It means that far fewer neutrons strike unit area of an instrument per unit dose equivalent. Hence, to generate a useful count rate at normal occupational dose rates an instrument has to be relatively large and the detection efficiency has to be much larger, when compared to most x, gamma detectors.

Unfortunately, the response of the majority of instruments is still very low, typically 0.3 $s^{-1}/(\mu Sv\ h^{-1})$, about 20% of the response of the industry standard energy compensated GM detector for x, gamma radiation.

Suitable instrument types

There is a variety of instrument types available, but the vast majority of radiation protection measurements are performed using some form of thermal (ie very low) energy detector surrounded by a large mass of polyethylene, the moderator. This mass thermalises high energy neutrons by forcing them to undergo multiple collisions until their energy is reduced to the energy that would be predicted by the ambient temperature. The thermal neutron detector can be a BF_3 proportional counter, a ^3He proportional counter or a lithium iodide scintillator doped with europium, within the moderator, which is a cylinder or sphere of polyethylene. Within the moderator there is often a layer of neutron absorbing material, such as boron loaded plastic, which is used to improve the energy response.

The energy response of neutron monitors is much poorer than for x, gamma monitors. Examples are shown in Figure A1 for some common instruments. The extreme over-response at intermediate energies when compared to the high energy (≈1 MeV) and thermal (0.025 eV) responses should be noted. The problem is obviously more difficult than for x, gamma radiation because of the much wider energy range, 0.025 eV to 10 MeV, a range of 4 10^8, compared to the

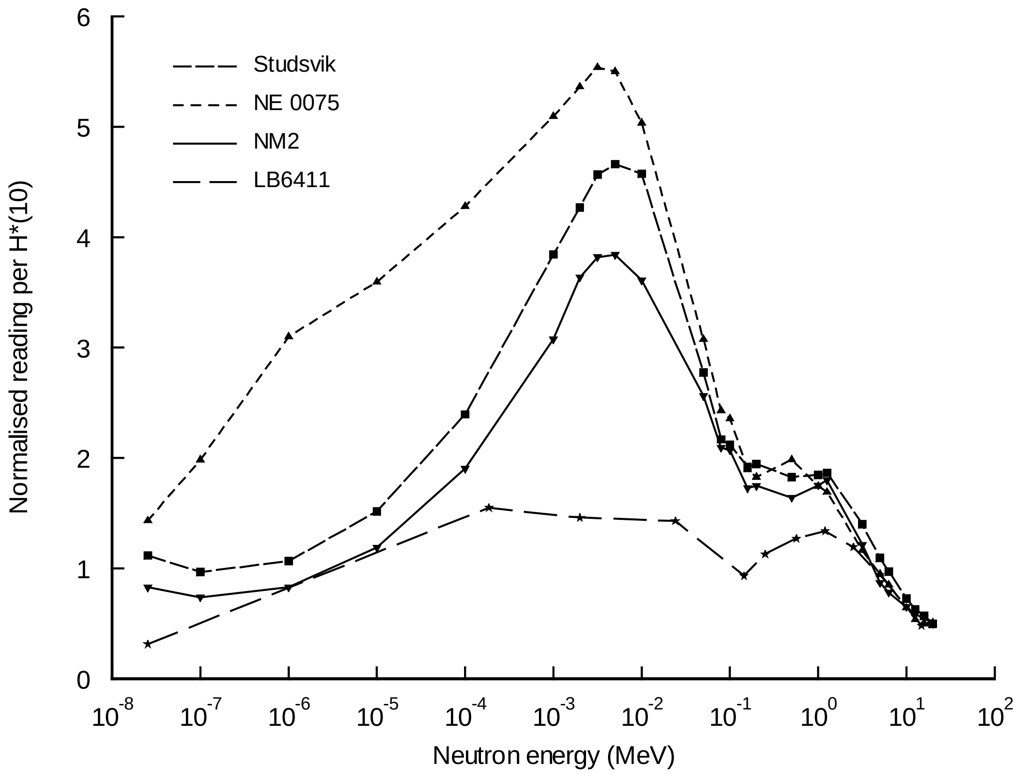

FIGURE A1 Energy response for some commom instruments

5 keV to 3 MeV range usually considered important for x, gamma monitoring, a range of 600. The over-response is also generally unimportant in practical monitoring because the majority of practical spectra are composed of a high energy component and a thermal component, with little in between. There are, as always, exceptions.

The detector is connected to a ratemeter or scaler-timer. This contains a discriminator which rejects the small pulses produced by x and gamma radiation and only accepts the much larger pulses produced by neutron interactions. In essence, the ratemeter is very similar to those found in proportional counter based contamination monitors. The major problem is how to deal with the relatively low count rate expected at normal operational levels approximately 0.3 $s^{-1}/(\mu Sv\ h^{-1})$. At 7.5 $\mu Sv\ h^{-1}$ this corresponds to only 2.3 pulses per second. The count rate from the industry standard ZP1202 GM detector at the same dose equivalent rate from gamma radiation is 12 pulses per second. There are two approaches to this. One is to use a very long time constant ratemeter, which averages over a long period to give a reasonably constant indication. The disadvantage of this is that the user has to wait at least three time constants after moving position before recording the indication. The other solution is to use some variation of the cycling scaler, where the instrument counts for a fixed time and then displays the answer. The time can be selected to provide a suitable statistical precision. For example, for an instrument with a nominal sensitivity of 0.3 $s^{-1}/(\mu Sv\ h^{-1})$, a counting time of 33 seconds at a dose equivalent rate of 7.5 $\mu Sv\ h^{-1}$ will give an average close to 75 counts. This can be displayed as 7.5 to give a direct indication of dose equivalent rate.

Suitable instruments

- Spherical 210 mm diameter moderator, BF_3 proportional counter.
- Spherical 210 mm diameter moderator, ^3He counter.
- Spherical 210 mm diameter moderator, LiI(Eu) scintillator.
- Cylindrical moderator (≈215 mm diameter, ≈250 mm long) moderator, BF_3 proportional counter.

Generally the best

- Where portability dominates, generally the 210 mm diameter moderator BF_3 detector type, provided the radiation spectrum is not thought to contain a large component above 1 MeV.
- Where the spectrum is complicated, the large cylindrical moderator BF_3 detector type.

Survey procedure

This follows the same general procedure as in the monitoring of x, gamma radiation. The main differences are the weight of any of these instruments and the low sensitivity. At low dose equivalent rates, <20 $\mu Sv\ h^{-1}$, a stool or tripod can be useful to support the instrument. At lower dose equivalent rates, the instrument has to have either a very long response time or some form of scaler-timer.

A16 Alpha contamination

Alpha emitting nuclides tend to have relatively high radiotoxicities. The alpha emissions also have a very short range. The first characteristic means that acceptable maximum surface activity levels are very low, with many organisations working to a maximum level of 0.4 Bq cm^{-2}. The second characteristic means that any coating of paint, grease or polish over the contaminated surface will attenuate the alpha radiation considerably and also demands that monitoring is carried out very close to the surface, normally with the probe about 3 mm from the surface. The energy range of alpha disintegrations is relatively narrow, covering 4 to 8 MeV. This should be contrasted with beta radiation, which covers a range from 18 keV maximum energy to in excess of 3 MeV and with photon radiation, which covers the range 5 keV to tens of MeV. This limited energy range means that all alpha emitters tend to be treated as the same, which is regrettable as the range of a ^{238}U alpha particle is less than half that of the more energetic particles.

Direct monitoring is only possible where the alpha activity is directly on the surface. Material such as stainless steel, melamine faced boards and intact paint are normally satisfactory. Surfaces such as plaster, concrete, soil and wood are not.

Suitable instruments

- Zinc sulphide scintillation detectors.
- Dual phosphor probes, comprising a layer of zinc sulphide on a thin plastic scintillator plate.
- Solid state alpha detectors.
- Gas refillable proportional counters.

Generally the best

- There is no clear choice. The instrument characteristics should be considered in the light of the monitoring circumstances.

Survey procedure

Alpha particles have an extremely short range, with a maximum in air of a few cm, even for a perfect source, ie one with an extremely thin layer of alpha emitting activity on the surface, not covered by even the thinnest layer of oil, grease or dirt. Practical monitoring distances have to be less than this, because the particle has to have sufficient energy to penetrate the detector window and also to generate a countable pulse. In practice, the count rate from an alpha source will drop off significantly with increased separation between the source and detector and will normally fall to zero by approximately 15 mm. As a consequence, monitoring is normally carried out with a probe to source spacing of about 3 mm, close enough to allow efficient detection from a clean source and far enough away to avoid contamination of the detector. Even then, the slightest covering of the source will make the alpha contamination undetectable. As an example, one coat of gloss paint will completely shield an alpha source, as will a barely perceptible film of grease or oil. Even a very thin coat of furniture polish will have a considerable effect.

The other significant problem is the generally low maximum level of acceptable surface alpha contamination, typically 0.4 Bq cm^{-2} or less. This low level means that any alpha detected has to be treated as significant. The surveyor must pause at the point where the event was detected and confirm that the average count rate is within the acceptable level. The one positive characteristic of alpha detectors is the very low background count rate, typically less than 0.1 s^{-1} for a 150 cm^2 detector. This means that two counts in adjacent seconds are likely not to be background and are probably due to contamination. A further problem is that even quite trivial levels of contamination on the probe will cause an unacceptably high background.

To summarise, the problems are as follows.

(a) Alpha particles can only be detected with the probe very close to the surface under examination.

(b) Even the slightest covering of grease, oil or paint over the contamination will attenuate the alpha particles to the point of making them undetectable.

(c) The process relies upon the normally very low background count rate from an alpha detector. Any contamination on the probe will be unacceptable in most circumstances.

Guiding a probe 3 mm above a surface demands a steady hand. When the area in question is likely to be clean then it is permissible to support the back of the detector using a finger tip rubbing gently on the surface. The surveyor should wear gloves and the detector must pass over the surface before the finger. Hence the finger should be rubbing on a surface which has been already monitored. The finger should be checked regularly for contamination.

The rate of movement should normally be a few cm s^{-1}, if the surveyor wishes to identify areas of approximately 100 cm^2 contaminated at a level of 0.4 Bq cm^{-2} or less. Alternatively, if an averaging area of 1000 cm^2 is being employed then movement can be faster. At this larger averaging area, a 10 cm x 15 cm detector, a typical size, can be moved quite fast, at up to 30 cm s^{-1}.

There are two basic forms of alpha monitor generally produced. These are the probe and ratemeter combination and the single-handed unit.

The probe and ratemeter type has the advantage that the probe is much lighter than the single-handed unit. This makes it easier to use over a long day. A separate probe also simplifies monitoring of difficult access areas, although the advantage is less than with other forms of monitoring because of the need to keep the probe close to the surface.

The single-handed form has the advantage that the user will have the ratemeter indication in view as he or she moves the detector window over the surface.

Monitoring should be performed mainly using the audio output. The instrument indication is generally only important when recording the maximum count rate from a relatively active area. For noisy areas a lightweight ratemeter is useful as the loudspeaker can be held close to an ear. Alternatively an earpiece can be used. Much alpha monitoring is performed using dual function detectors. It is important that alpha counts make a very different noise from a beta channel count, as a user will wish to distinguish the probably rare alpha event from the several counts per second produced by the beta channel, generated by the gamma background.

A17 Beta contamination monitoring for nuclides with a maximum energy equal to or greater than 0.16 MeV

Beta emitting nuclides in the form of liquid sources are used in large quantities in nuclear medicine and research. They will also be encountered in nuclear power stations as a consequence of activation of the core and in any work with nuclear fuel, either pre- or post-irradiation. Monitoring of people, surfaces and equipment for beta contamination is thus very common. Beta radiation differs from alpha radiation in two ways. One is the very wide spread of maximum energies of common nuclides, from ^{3}H at 18 keV to ^{32}P and ^{90}Y at over 2.2 MeV. The other is that beta emitting nuclides do not emit discrete energies. Each decay has a range of possible energy from essentially zero up to a defined maximum value. Generally the average energy is about 30% of the maximum for the decay. Another aspect which is different from alpha monitoring is that any detector will have a background count rate caused by gamma background and cosmic ray interactions. A typical value is one per second for every 20 or 30 cm^2 of detector. The surveyor thus does not have the luxury of considering any event detected as significant. To set against this, however, is the generally lower radiotoxicity of beta emitters compared to alpha emitters, which leads to generally higher maximum acceptable levels which, in turn, leads to generally higher limiting count rates.

The low energy cut-off suggested (0.16 MeV) is because below that energy the range of the average beta particle is insufficient to cross a typical 3 mm air gap and penetrate a detector window. Monitoring for lower energies generally uses wiping followed by liquid scintillation counting.

Suitable instruments

- Thin end window GM detectors.
- Thin glass or metal walled GM detectors.
- Gas refillable proportional counters.
- Thin window xenon filled sealed proportional counters.
- Thin windowed scintillation detectors.

Generally the best

- There is no clear choice. The instrument characteristics should be considered in the light of the monitoring circumstances. The most important parameter is the maximum energy of the beta emitter.The instrument has to have a useful response at that energy. The most restricted type is the thin glass or metal walled GM which can only be used for energies in excess of 0.5 MeV.

Survey procedure

For soft beta emitters the probe should be held about 3 mm from the surface, which is difficult to achieve for any length of time. When the area in question is likely to be uncontaminated or only very lightly contaminated then it is permissible to support the back of the detector using a fingertip resting gently on the surface. The surveyor should wear gloves and the detector must pass over the surface before the finger. This will identify any significantly contaminated areas before the finger touches them. The finger should be checked regularly for contamination.

For energetic beta emitters, such as ^{32}P or ^{90}Sr + ^{90}Y, a gap of 10 mm will not seriously attenuate the radiation. Hence the probe need not be held so close to the surface. Moving the probe away from the surface effectively increases the averaging area. For point contamination the count rate will drop off with increasing distance because of the consequences of the inverse square law. For contamination which is relatively uniform over a wide area no obvious drop off will be observed.

In contrast to alpha monitors, most large area beta probes will have a significant background count rate. At normal environmental levels this is about 1 s^{-1} for every 20 cm^2 of probe area.

When exposed to high energy gamma radiation the response is typically 5 $s^{-1}/(\mu Sv\ h^{-1})$ for every 20 cm^2 of probe area. This sensitivity inevitably limits the ability of the probe to detect contamination when monitoring is taking place in significant gamma radiation fields, by producing a general increase in background count rate. The most obvious example of this is the monitoring of transport packages which contain energetic beta emitters. This beta radiation is likely to be completely shielded. However, Bremsstrahlung x-rays will be produced which can give rise to a measurable dose rate on the outside of the package. For a typical package containing ^{32}P the surface dose rate can reach a few $\mu Sv\ h^{-1}$. This will produce a count rate on a 50 mm diameter pancake GM detector of about 25 s^{-1}. This count rate will also vary as the detector is moved over the surface of the box because the source to detector distance will change, even if only one source is present. As many of these packages contain more than one source then the count rate from the x-rays alone will vary in a complicated way over the bottom of the box. This high and varying count rate will mask contamination by ^{32}P at a level of a few Bq cm^{-2}. Direct monitoring of such packages is thus confined to the detection of relatively high levels of contamination. To avoid this problem the normal solution is to wipe the box and measure the wipe in a lower background area.

A18 X-ray and gamma contamination

Many nuclides produce low energy x-rays, typically by a process of electron capture. The nucleus captures an electron from the K shell, leaving a gap. This is then filled by an electron dropping down from a higher level. In doing so it sometimes produces an x-ray photon with an energy equal to the difference in energy levels. Such nuclides are popular in many research applications as they produce reasonably penetrating radiation, which can also be detected efficiently. An example is ^{125}I which produces a mixture of 27 to 32 keV x-rays and 35 keV gamma photons.

X-ray emitting nuclides can also be found in contamination around nuclear reactors, and are particularly prominent in AGRs. The most prominent nuclide is ^{55}Fe, which emits a 5.9 keV x-ray.

A less familiar application is for the detection of relatively gross levels of contamination by transuranic nuclides such as ^{239}Pu and ^{241}Am. Many transuranics decay by alpha emissions which are very easily shielded. If contamination is suspected but the surface in question is dirty or greasy then a check for relatively high levels of activity, typically from a few Bq cm^{-2} upwards, can be made by looking for x-rays in the 13 to 20 keV range. These are generated by electrons dropping down into the L shell, rather than the K shell. These x-rays are relatively penetrating and will pass through a thin layer of grease or oil almost unattenuated. They will also pass, to a degree, through paint but will be attenuated by the pigment which is usually titanium or, in older paint, lead based.

Most gamma emitters also emit beta radiation and, generally, it is the beta radiation which is used in contamination monitoring. Typical examples are ^{137}Cs and ^{60}Co. However, there are relatively rare examples which do not emit beta radiation or, rather more correctly, where the beta decay stage has already taken place. Most common is ^{99m}Tc, which is used in large quantities in medical imaging. This emits a 140 keV photon.

It is also, obviously, possible to monitor surface contamination by the beta + gamma emitting nuclides using the gamma radiation. This is not done normally for higher energy emitters simply because the gamma radiation is too penetrating. To detect it efficiently demands a large area, high mass detector, which leads automatically to a high response to background gamma and cosmic radiation. As an example, a typical 50 mm diameter, 50 mm thick sodium iodide detector will have a background of 50 s^{-1}. In comparison, a typical 50 mm diameter thin end window pancake GM detector will have a background of 0.5 s^{-1}, a factor of 100 lower. Hence, this section will concentrate on the detection of relatively low energy x, gamma radiation covering the range 5 to 140 keV.

There are two main problems. At the low energy end the window covering the detector has to be relatively thin and have a low atomic number to give a good transmission. At the high energy end the problem is to stop the relatively penetrating radiation. This demands a high mass per unit area, high atomic number detector. There are two popular forms. One is the xenon filled, titanium windowed proportional counter. The other is the aluminium or beryllium windowed sodium iodide scintillation detector.

Suitable instruments

- Xenon filled, titanium windowed proportional counter.
- Aluminium or beryllium windowed sodium iodide detectors.

Generally the best

- There is no clear choice. The instrument characteristics should be considered in the light of the monitoring circumstances. See Appendix C.

Survey procedure

Even low energy (5.9 keV) x-radiation has a much longer range than alpha or low energy beta radiation. Hence the need to hold the detector very close to a surface is reduced. In a similar way to high energy beta radiation, drawing back a few mm from a surface effectively increases the averaging area, reducing the count rate from point source contamination but having little effect on distributed contamination. Monitoring is thus generally similar to dealing with high energy beta radiation. The probe should be scanned over the surface in question while the operator listens to the audio output. If an increase is noted or if a trigger point is exceeded then the operator should move the probe to maximise the count rate, and either record the value and position or clean up the contamination immediately. The main problem is the calculation of the expected response to a particular nuclide. Many have complicated decay schemes, generating a range of energies. There is also a rather poor set of calibration sources in comparison with alpha and beta contamination. Manufacturers can often supply typical response data for a range of nuclides but, in the absence of specific information, frequently the best that can be done easily is to confirm that the instrument should have a significant response to at least a significant proportion of the radiations present. This will give the user the confidence that the instrument will detect significant contamination, although quantifying it will not be easily achieved. Alternatively, it may be possible, if facilities are available, to make a calibration source by spotting known activity solution on to a suitable surface. The response of the instrument can be calculated and noted for future reference.

One other aspect which is generally more of a problem than for alpha and beta radiation is the influence of stock solutions of the nuclide on the bench or in the room. Often these generate a significant background level which makes direct local monitoring difficult. If the solutions cannot be removed or better shielded then it may be necessary to take wipes for monitoring in a lower background area. The same problem is also present when monitoring packages.

A19 References

1 Hubbell J H and Seltzer S M. Tables of x-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV to 20 MeV for elements *Z* = 1 to 92 and 48 additional substances of dosimetric interest. Washington DC, US Department of Commerce, NISTIR 5632 (1995).

2 HMIP. Routine measurement of gamma ray air kerma rate in the environment. London, HMSO, Technical Guidance Note (Monitoring) M5 (1995).

APPENDIX B
Hints on Establishing Radiation Type and Energy

In many circumstances there is no debate on the dominant radiation types and energies present. Good examples of this are open shop radiography using an ^{192}Ir gamma source and contamination monitoring in a radiopharmacy that uses only ^{125}I. However, in many circumstances, things are more complicated. These have been noted in earlier sections where, for example, the energy of an x-ray beam may be in debate because of scatter or hardening via transmission or where there may be a mixture of radiation types produced by a beta thickness gauge.

B1 X-radiation energy

X-rays tend to be softened by scatter and hardened by transmission. Often a user might wish to employ a steel walled energy compensated GM based detector, because of its low cost and operational convenience, but is concerned because there may be a significant component below 50 keV, to which the energy compensated GM will not respond. What possibilities are there to identify whether such an instrument is acceptable? The simplest one is to compare the indication of the instrument in question with one with better metrological qualities such as an ionisation chamber. If the user makes measurements at each point of interest with the two instruments then an intercomparison of the results will clearly identify any points where the energy compensated steel walled GM produces a significantly lower indication. If there is no such point, then the GM based instrument is acceptable. If there are, then an instrument of better metrological quality will be required, such as an ionisation chamber or a thin window energy compensated GM detector.

An alternative route is to use an ionisation chamber instrument of good quality and a 0.5 mm thick copper filter. If the user goes to each monitoring point and performs a measurement with and without the copper filter then an intercomparison of the results will show points where a conventional steel walled energy compensated GM detector cannot be used. These will be where the indication with the filter between the source and the open window of the ion chamber (slide open or cap off) is less than 50% of the corresponding reading without the copper filter. The rationale behind this is that the energy response of the ion chamber with the filter will be very close to that of a good quality energy compensated steel walled GM detector. If no large differences appear, then the GM unit can be used.

To illustrate this point the transmission of the copper filter is given below.

Energy (keV)	Transmission of a 0.5 mm thick Cu filter
20	$1.5\ 10^{-6}$
30	$1.2\ 10^{-2}$
40	0.14
50	0.35
60	0.53
80	0.75
100	0.85

B2 Estimation of beta energy

It may be useful to have some feel for the energy of a beta radiation field. For example, a user may wish to use a thin end window GM detector to determine the directional dose equivalent rate with reasonable accuracy. The response of such a detector varies by about a factor of two over the normal energy range of interest for beta dose rate measurements. The values below will help to make an estimate of the radiation energy. These were derived using an NPL beta protection level secondary standard to produce the radiation field and a Mini Instruments 900 EP15 thin window pancake GM survey instrument.

Nuclide	E_{max} (MeV)	Transmission of 1 mm polyethylene
^{90}Sr + ^{90}Y	2.27 + 0.54	0.3
^{85}Kr	0.67	0.05
^{147}Pm	0.225	<0.01

It should be noted that polyethylene was chosen for its good transmission of x-radiation. If there is a large x-ray (Bremsstrahlung) component then transmissions will be high. Identifying the relative components is described in the subsequent section.

B3 Identifying the presence of x-radiation in the presence of beta radiation

The process relies upon the fact that the transmission of beta radiation depends mainly on the mass per unit area of the material between source and detector, and only to a small degree on its atomic number. The transmission of low energy x and gamma radiation, however, depends greatly on the atomic number of the filter.

Convenient filters are given below. Again the transmissions were measured using a Mini Instruments 900 EP15. The filter materials have a transmission of about 0.04 for ^{90}Sr + ^{90}Y beta radiation and lower for lower energies. The other filter required is 4 mm PMMA (Perspex). This has a similar beta transmission.

x, gamma energy (keV)	Transmission of		
	0.5 mm Cu	1.8 mm Al	4 mm PMMA
15	0	0.03	0.69
20	0	0.22	0.97
30	0.03	0.63	1
40	0.22	0.81	1
50	0.45	0.88	1
60	0.62	0.95	1

These filters can clearly help to identify whether the field is mainly beta radiation and whether it has a significant x, gamma component, and determine its effective photon energy, at least approximately. This level of information will usually be sufficient to allow a sensible choice of monitoring equipment and a sensible choice of correction factor, if needed at all.

This process will not work where, for example, there are two widely separated gamma energies contributions such as ^{137}Cs (662 keV) and ^{241}Am (60 keV) but will work where there is a mixture of Bremsstrahlung and beta radiation.

Alternatively, an easy qualitative test is to use a detector with a very poor beta response and a very high x, gamma response, such as a sodium iodide detector with a thick plastic end cap. This will clearly indicate the presence of x, gamma radiation even in the presence of a relatively high beta intensity. However, the results will be difficult to interpret quantitatively.

B4 Gaining information on mixed contamination

Sometimes, particularly in older facilities undergoing decommissioning, it is useful to be able to identify, broadly, the contaminants present.

Easy first separations are into alpha, beta and x, gamma emitters. Alpha emitters are relatively easily identified because only they will cause a count rate in a correctly set up alpha probe. Similarly, low energy x, gamma emitters can clearly be identified because they will produce a very much higher count rate on a thin sodium iodide scintillation detector than on any beta scintillation, GM or gas refillable proportioned counter detector.

If the potential beta contaminants are reasonably energetic, with E_{max} from 0.3 MeV upwards, then the alpha contribution to a typical beta detector can be removed simply by making measurements with a 15 mm surface to probe spacing. This will normally reduce the alpha contribution to close to zero while not greatly affecting the beta signal.

B5 Estimating beta contamination energy

Often it will be useful to be able to make a crude estimate of the energy of a beta contaminant. This is reasonably easy to do where there is one dominant nuclide, but care should be taken where there is a complicated mixture. The results below were obtained using paper absorbers, but any other similar material, such as polythylene food bags or cling film will do, provided the mass per unit area can be estimated. The paper used had a thickness of 6 mg cm^{-2}, equivalent to 60 g m^{-2}.

Again a Mini Instruments 900 EP15 was used.

Nuclide	E_{max} (MeV)	Half thickness (mg cm^{-2})	Quarter thickness (mg cm^{-2})	Tenth thickness (mg cm^{-2})
^{90}Sr + ^{90}Y	0.54 + 2.27	24	96	–
^{36}Cl	0.69	23	46	70
^{60}Co	0.31	5	11	25
^{147}Pm	0.225	3	6	10
^{14}C	0.167	–	–	6

B6 Estimating the energy of a gamma source

Sometimes, particularly in NAIR incidents or when decommissioning facilities, it will be convenient to estimate the energy of a gamma source. This can be done using lead filters. Lead is easily available from most builders' merchants in a range of thicknesses and of sufficient purity for this purpose. Any gamma detector can be used provided its response is not violently energy dependent, such as thin sodium iodide scintillation detectors. Thick ones, eg 50 mm x 50 mm, are acceptable, as are any GM detector and ionisation chamber.

This process is not accurate but can be used to differentiate between ^{60}Co, from activation, 1.25 MeV average, and ^{137}Cs, from contamination, 662 keV, for example. It can also be used to identify an ^{241}Am smoke detector from a ^{226}Ra based example, as 1 mm of lead will completely shield an ^{241}Am gamma source but will have only a limited influence on the ^{226}Ra one.

Nuclide	E (MeV)	Half-value thickness (mm Pb)
^{60}Co	1.17 + 1.33	16
^{131}I	0.36–0.72	3
^{137}Cs	0.662	8
^{192}Ir	0.32–0.61	3
^{226}Ra	Various to 2.09	12

APPENDIX C
Summary of Instrument Characteristics

C1 Conventional energy compensated GM detector

Good points

- Compact for a particular sensitivity, compared to ion chambers.
- Electronically simple.
- Low maintenance.
- Tough, when well designed.
- Popular and inexpensive.
- Easy to couple to an audio output.
- Adequate energy and polar response if well designed.
- Will withstand very high dose rates in the case of equipment failure.

Weaknesses

- Responds only to x, gamma radiation above 50 keV. They will under-respond significantly in an unfiltered x-ray beam for potentials less than 150 kV.
- A vigorous over-response, by up to a factor of two for very high energy (>3 MeV) x, gamma radiation
- Pulsed sources – there is a count rate limitation when used with pulsed sources. For pulsed sources producing narrow (up to tens of microsecond) pulses it is important that the count rate from the detector does not exceed 30% of the pulse repetition frequency, otherwise the instrument will under-read. Hence it is essential to know the sensitivity of the instrument [in counts $s^{-1}/(\mu Sv\ h^{-1})$] and to identify a maximum trustworthy count rate. This leads to the unfortunate circumstances that the higher the sensitivity, the lower the maximum useful indication.
- Pulsed sources will give a completely false reading at high dose rates, for example close to the target in the main beam. At the ultimate the detector will record one pulse per radiation pulse. For a 400 Hz machine this means a maximum count rate of 400 s^{-1}. If a relatively high sensitivity detector is used, for example one giving 5 $s^{-1}/(\mu Sv\ h^{-1})$, then that gives an ultimate indication, at no matter how intense a dose rate, of 80 $\mu Sv\ h^{-1}$.

Check for

- Adequate sensitivity. For reasonably quick monitoring a minimum count rate of at least 3 s^{-1} and preferably 5 s^{-1} is required. Higher is better. For 7.5 $\mu Sv\ h^{-1}$ choose a detector giving at least 0.8 $s^{-1}/(\mu Sv\ h^{-1})$. For 2.5 $\mu Sv\ h^{-1}$ choose one giving at least 2 $s^{-1}/(\mu Sv\ h^{-1})$.
- A decent ambient dose equivalent rate response from 50 keV to 1.25 MeV (within ±25% compared to ^{137}Cs gamma radiation).
- A reasonable polar response. When tested at 60 keV the response should be within ±25% of that in the reference direction when tested out to 45° off axis.
- No fall back at high dose rates. There is no technical reason why a GM based instrument should fail to danger below 1 $Sv\ h^{-1}$.

C2 Thin window energy compensated GM detectors

Good points

- Compact for a particular sensitivity compared to ion chamber types.
- Electronically simple.
- Low maintenance.
- Very wide energy response for x, gamma radiation, 10 keV upwards.
- Inexpensive.
- Easy to couple to an audio output.
- Detector can be mounted on a probe, which can be steered round complicated objects.

Weaknesses

- Responds effectively only to x, gamma radiation.
- Slightly less robust than conventional energy compensated GM instruments.
- Similar problems as for conventional energy compensated GM instruments at high energies and when dealing with pulsed sources.

Check for

- Adequate sensitivity. Aim for a count rate at the lowest dose rate of interest of at least 3 s^{-1}.
- As for conventional energy compensated GM instruments, except for the wider energy range, 10 keV to1.25 MeV.

C3 Thin end window GM detectors

Good points

- A reasonably high sensitivity to a wide range of x-ray energies.
- Responds to beta radiation.
- Electronically simple.
- Low maintenance.
- Inexpensive (≈£100).
- The detector is normally on a probe, which can be steered round complicated objects.
- A good audio output, which means the user can concentrate on steering the probe and only has to read the display when an elevated count rate is located.

Weaknesses

- X-radiation response is energy dependent typically over a range of about four from the minimum, usually taken as ^{137}Cs gamma radiation (662 keV), to the maximum, at approximately 60 keV, falling slowly for lower energies. For estimating directional dose equivalent rates in mixed beta and x, gamma fields the normal approach is to use the ^{137}Cs gamma response factor, which is generally close to the response for energetic betas (^{90}Sr + ^{90}Y) and not more than twice the response for betas of lower energy. In this way the instrument may slightly under-respond for beta radiation and will generally over-respond for the Bremsstrahlung.
- Very vulnerable to window damage. A typical 1 mg cm^{-2} window can be punctured by a cut-off rye grass stalk, as well as obviously potentially damaging objects such as tweezers and screwdrivers. However, for x-ray measurements, the protective cap can normally be

left in place, provided the energy response is known for the cap on and provided the user is confident that really low energies, ie those below 15 keV, are not likely to be present. Above that energy a typical plastic cap provides very little attenuation.

- Relatively high repair costs. The only solution to a damaged detector is complete replacement, unlike some other contamination monitor types which can be refurbished.

Check for

- X, gamma radiation – polar response. The best shape of detector is one with a window diameter which is large compared to the detector depth. For that shape the response is not violently directional. For long thin detectors at low energies the response is very directional. Hence, to make a sensible measurement of leakage radiation, such a detector has to be in the right place and pointing in the right direction.
- Beta contamination monitoring – sufficient size. The industry standard has a 50 mm diameter end window. Smaller ones make for very labour intensive monitoring and should only be used when monitoring difficult and complicated objects.
- Good grille. The detectors are very vulnerable and should normally be protected by a fine etched mesh grille. Wire grilles are less transparent, particularly to betas arriving at shallow angles. Open mesh grilles generally lead to high damage rates but can be useful when monitoring smooth surfaces at very low levels.
- A good performance at the lowest energy of interest. This low energy defines the maximum window thickness. The performance of the detector drops as the beta energy decreases. Generally such detectors are useable down to 0.17 MeV (^{14}C, ^{35}S) at a limit of 4 Bq cm^{-2}.
- The correct shape. Detectors should have a window diameter greater than the detector depth. Deep detectors lead to higher background count rates, increasing the maximum missable activity. The normal term for a detector with a high diameter to depth ratio is a pancake detector.

C4 Large energy compensated GM detector connector to a scaler-timer for environmental air kerma rate measurements

Normally this employs a ZP1221/01 or similar energy compensated GM detector.

Good points

- Adequate sensitivity, ≈16 $s^{-1}/(\mu Gy\ h^{-1})$.
- A reasonably low self dose rate, typically 0.2 pulses per second compared to the 1 to 2 pulses per second produced by cosmic and environmental gamma radiation.
- Electronically simple.
- Low maintenance.
- Extremely light.
- Easy to mount on a tripod.
- Low cost.

Weaknesses

- The response rises sharply above 1 MeV. See Figure C1. This can cause problems in the presence of very high energy gamma radiation, such as the 6 to 7 MeV radiation from ^{16}N.
- The detector is not completely robust but can be protected by foam.

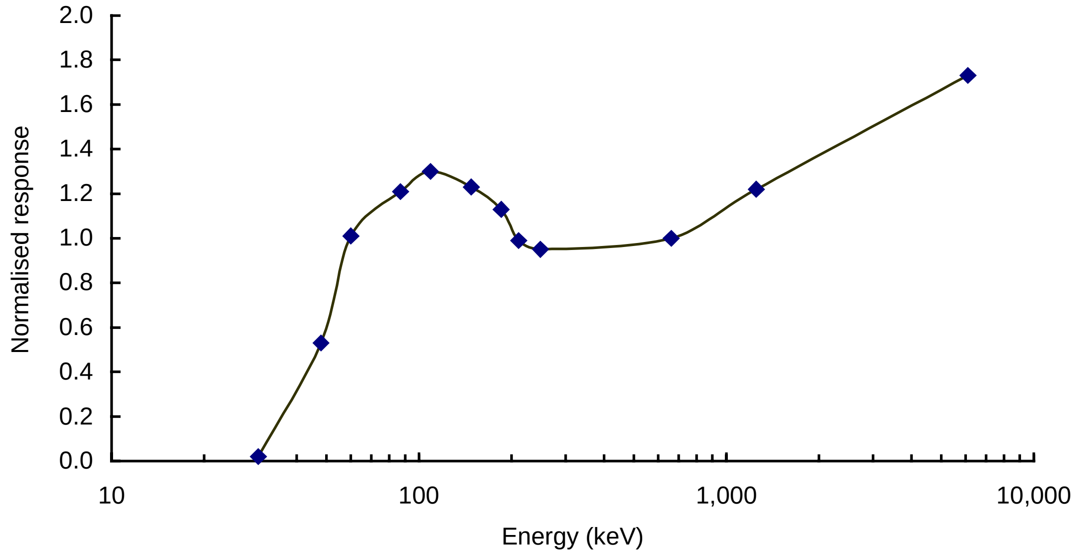

FIGURE C1 X and gamma air kerma response of a ZP1221/01 energy compensated GM detector

Check for

- A creeping increase in background count rate, particularly when the detector is left powered for months.
- A tendency for the count rate to change with temperature, particularly when the detector is continuously powered.
- A gradual fading away after an impact. Dropping the probe can cause cracks in glass or ceramic seals, leading to loss of function over days and weeks.

C5 Thin glass or metal walled GM detectors

These are generally cylindrical with a glass or metal wall with a thickness of approximately 30 mg cm^{-2}, a length of 10 to 20 cm and a diameter of approximately 15 mm.

Good points

- Reasonably robust when compared with thin window detectors.
- Electronically simple.
- Inexpensive to buy.
- Easy to couple to an audio output.
- Light.

Weaknesses

- A relatively high minimum useful beta E_{max}, generally approximately 0.5 MeV.
- A rather undefined monitoring area. An end window detector held close to a beta contaminated surface will, for monitoring purposes, only respond to activity directly below the window as the thick side walls will screen out particles from further away. With a cylindrical geometry, even in a shielded probe, most designs will respond to particles incident at shallow angles and hence from far away.
- Relatively high background count rate per unit contamination sensitivity.

Check for

- Halogen filling. These operate over a wide temperature range and have very long lifetimes. Organic filled detectors, while easier to make and cheaper, are generally less reliable and are shorter lived.

C6 Ionisation chambers

Good points

- Excellent x, gamma ambient dose equivalent energy and polar response generally (slide shut).
- Good beta directional dose equivalent energy and polar response generally (slide open).
- No significant dose rate limitations normally.

Weaknesses

- Bigger and clumsier than energy compensated GM types.
- More expensive.
- Generally more sluggish at low dose rates
- Relatively insensitive and subject to higher background fluctuations than other dose rate monitors.
- Large averaging area for a given sensitivity which may lead to much lower indicated dose rates than end window GM detectors, for example, when monitoring narrow beams.
- Require more maintenance.
- Generally no audio output.
- May change range or function unexpectedly if strong magnetic fields are encountered.

Check for

- Adequate sensitivity – it is important that, at levels at which barriers are to be set etc, the instrument indication is readable. On analogue instruments the minimum level of use should be at least 25% of the lowest dose rate range scale maximum.
- Problems associated with any magnetic fields.
- Low area instruments with an apparently high sensitivity.
- Ion chambers with a 10 cm^2 end window and a 10 $\mu Sv\ h^{-1}$ full-scale most sensitive range are available. However, they are very difficult to use, generally have a very high level of fluctuation at background levels and need careful maintenance.

C7 High pressure ionisation chamber instruments

These use high volume (>5 litres), high pressure (~10 atmospheres) steel walled ion chambers.

Good points

- A good energy response, above approximately 80 keV.
- Adequate sensitivity.

Weaknesses

- The detector is a pressure vessel which cannot be transported by air without special precautions.
- Extremely heavy.

- Bulky detector.
- Very expensive.

C8 Large energy compensated proportional counter detector connected to a scaler-timer

Good points

- Adequate sensitivity.
- Low self dose.
- Good energy response, extending to lower energies than the GM detector types.
- Low maintenance.
- Extremely light.
- Easy to mount on a tripod.

Weaknesses

- Electronically more complicated than GM detector types.

Check for

- Gradual loss in sensitivity with time.

C9 Scintillation based dose rate monitors

These are instruments fitted with plastic scintillators and marked in μSv h^{-1}. These are not sodium iodide based instruments marked in counts per second.

Good points

- Very good x, gamma sensitivity, giving a very fast response and a very steady reading at 2.5 and 7.5 μSv h^{-1}.
- Good x, gamma energy and polar responses.

Weaknesses

- Much more expensive.
- More difficult to set up and maintain.
- Likely to require occasional adjustment throughout their lives.
- Generally no audio output.
- May behave oddly in pulsed fields as the instrument struggles to cope with the relatively high dose rate in the pulse followed by a much longer period at background levels.
- Generally only available as a single-handed unit, not as a probe and ratemeter combination.

Check for

- Low energy performance. Energy responses are often given on logarithmic graphs with sparse markings. When dealing with low energy sources it is important to confirm that the energy and polar response is adequate.

C10 Large plastic scintillator instruments for the detection of lost sources etc

These use large blocks of plastic scintillant. The detection probability is less per unit volume than for sodium iodide because the detector density is less and the atomic number is lower. However, the scintillator is generally much bigger.

Good points

- High sensitivity for large sizes. Typically volumes of 500 cm^3 upwards are used.
- Easy to couple to an audio output.
- Very tough detector.

Weaknesses

- No photopeak, ie full energy peak, but energy information can be derived from the position of the compton edge.
- Lower light output per unit energy deposited so the electronics have to work harder.
- Sensitive to magnetic fields.

Check for

- Adequate sensitivity.

C11 Large sodium or caesium iodide scintillation detector based instruments, for lost source detection

Good points

- High sensitivity, with approaching 70% detection efficiency even for high energy gamma radiation for 51 mm x 51 mm crystals.
- Electronically reasonably simple.
- Easy to couple to an audio output.
- Can be connected to a single channel analyser to reduce background and improve detection efficiency.
- Can be connected to a multi-channel analyser to produce nuclide identification.

Weaknesses

- Expensive.
- Heavy compared to normal radiation protection equipment.
- Fragile, particularly the sodium iodide crystal, less so the caesium iodide type.
- May be corrupted by strong magnetic fields.

Check for

- An adequately low energy threshold. For general monitoring a threshold of 60 keV is useful and easy to set using ^{241}Am gamma radiation.
- Sensitivity – it should be close to values given in standard texts. Low backgrounds or sensitivities indicate detector damage.

C12 Aluminium and beryllium thin windowed thin crystal sodium iodide detectors

These generally comprise a thin sodium iodide crystal, typically 3 mm thick and 20 to 150 mm in diameter, protected by a thin aluminium or beryllium window. Aluminium is used for detectors with a minimum energy of use of approximately 10 keV, while the more expensive and toxic beryllium is used for detectors which have to operate at lower energies.

Good points

- A good detection efficiency over a wide energy range, up to at least 140 keV.
- An extremely high sensitivity typically in the hundreds or thousands of counts $s^{-1}/(\mu Sv\ h^{-1})$ for low energy x-ray detection.

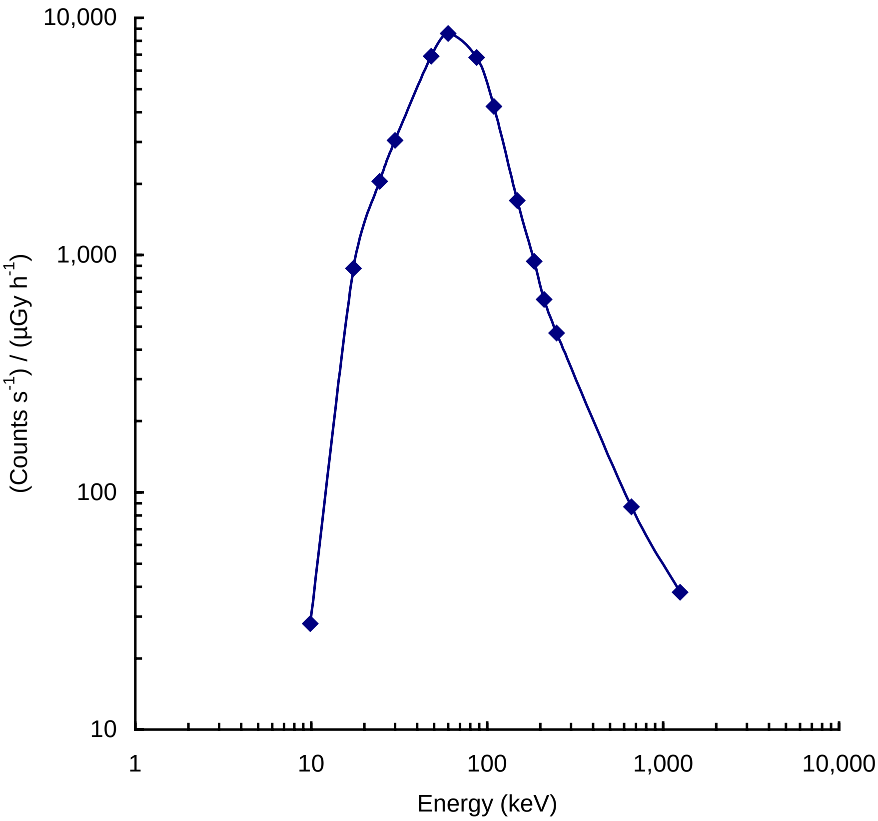

FIGURE C2 Typical response of a thin sodium iodide scintillation detector for x and gamma air kerma rate

- Reasonably tough – the windows are unpressurised and thicker than the xenon filled proportional counters and will not puncture when tapped with a pair of blunt nosed tweezers, for example.
- Can be used very effectively with counting energy windows to reduce background.
- A good audio output. For dose rate monitoring normally the best process is to concentrate on guiding the probe around the object of interest. The very high sensitivity means that even small defects will give a very clear burst of clicks. The surveyor can then pause, move the probe around to maximise the indication and then record the answer.

Weaknesses

- A very rapid change in response with energy when measuring dose rate. See Figure C2.
- The sodium iodide crystal is easily shattered and is also hygroscopic. Sharp knocks will cause the crystal to craze, greatly reducing the light gathering efficiency. Any sort of possible moisture ingress will result in yellowing of the crystal, again reducing the light gathering efficiency. This is expressed as an increase in the counting threshold energy.
- Operating voltage is very variable. In common with other photomultiplier based devices the correct operating voltage can range from 600 to 1200 V.
- Susceptible to strong magnetic fields, although the best examples have a mu-metal shield around the photomultiplier, which helps greatly.
- Background count rate is higher per unit area than proportional counters.
- More expensive than GM units for dose rate monitoring.

Check for

- Confirmation that the energy threshold, ie the minimum energy which the instrument can detect, is low enough. Each probe requires individual setting up. There is also a limited number of test radionuclides which generate low energy radiations which can be used for setting up. This is different from other instrument types, such as GM, ion chamber and plastic scintillator types, where the energy response does not depend on the operating voltage.
- A good polar response. Instruments with the crystal mounted at the very end of the detector always have good polar responses. Some have the crystal within a collimator. This reduces the background, but also gives a very directional response which means that the detector has to be in the right place and pointing in the right direction to give meaningful results.
- Excessive sensitivity when monitoring x-ray dose rate. If significant radiation levels are anticipated, will the instrument go to full-scale deflection? This is a strong possibility for higher voltage electron microscopes, for example.

C13 Zinc sulphide scintillation detectors

Good points

- Very efficient alpha detector.
- Available in reasonably large sizes, up to 20 cm x 30 cm.
- Good beta and gamma rejection.
- Virtually zero background count rate. Every event can be treated as potentially significant.
- Available as both probe and ratemeter and combined units.
- Audio output always available.
- Competitive price.

Weaknesses

- The optimum operating voltage is variable, even within one type of probe.
- Susceptible to damage to the very thin foil covering the scintillator plate which can lead to erratic performance as a result of light getting in to the detector (rugged versions are available but are more expensive).
- Susceptible to strong magnetic fields.

Check for

- Older instruments that fail to danger when there is a light leak.
- Detectors with excessively patched foils. Normally one or two small particles over points where the window has been damaged are acceptable.
- Poor uniformity of response over the area of the detector caused by poor light collection or scintillator deterioration.
- Correct operating potential. When in use for confirming the absence of alpha contamination in a low beta and gamma background the operating voltage should be set close to the point where background becomes noticeable, >0.1 s^{-1}. When used in areas of high gamma background or in the presence of beta contamination the operating voltage should be lower to avoid background counts. This, however, will reduce the sensitivity to alpha activity, particularly for lower energy and dirty sources.

C14 Dual phosphor probes, comprising a layer of zinc sulphide on a thin plastic scintillator plate

These offer dual monitoring of alpha and medium to high energy beta contamination.

Good points

- Dual function.
- Available in reasonably large sizes.
- Virtually zero alpha background count rate in normal gamma backgrounds.
- Audio output available with a different sound used to indicate alpha and beta pulses.
- Window easy to replace.

Weaknesses

- More susceptible to influence from beta and gamma radiation.
- More complicated, with a more demanding setting up procedure.
- Variable operating voltage between examples.
- Beta detection efficiency is poorer than both gas filled detectors and most beta only scintillation detectors.
- Susceptible to window damage (rugged versions are becoming available).
- While beta radiation should rarely cause an alpha count, a good proportion of the alpha radiation will cause a count in the beta channel. The dirtier the source, in the sense of the thickness of grime or grease covering the activity, the larger the proportion that enters the beta channel.
- Susceptible to magnetic fields.

Check for

- Light leaks.
- Detectors with excessively patched foils.
- Poor uniformity of detection, particularly in the corners of the probe.

C15 Solid state alpha detectors

These use large area silicon diodes as the sensitive element.

Good points

- Compact, as no photomultiplier tube is required, unlike scintillation detectors.
- No gas filling is required, unlike thin window proportional counters.
- Lightweight.

Weaknesses

- No amplification in the detector itself which makes them particularly sensitive to interference from radiofrequency fields and magnetic fields.
- Light sensitive.
- Expensive detector.

Check for

- Magnetic fields and radiofrequency fields which may corrupt monitoring results.

C16 Gas refillable proportional counters

These use a large area, often 10 cm x 15 cm, thin windowed gas filled proportional counter. The hand-held ones generally use butane lighter fuel as a counting gas. The detector requires regular refreshing, either from an external tin or from a built in reservoir.

Good points

- Large size.
- Good uniformity of response.
- Good alpha and beta detection efficiency over a wide range, covering beta emitters with maximum energies from ^{14}C (0.167 MeV) upwards.
- Relatively compact (no photomultiplier tube).
- Easy window repair.
- Detector can be rewired.

Weaknesses

- Needs regular gas refilling and refreshing.

C17 Thin window xenon filled sealed proportional counters

These are generally 10 cm x 10 cm or larger xenon filled proportional counters with titanium windows about 5 mg cm^{-2} thick.

Good points

- Can be obtained in large sizes.
- Also sensitive to low energy x, gamma emitters such as ^{125}I and ^{55}Fe.
- Can be re-windowed, although the cost is a large fraction of a new detector.
- Tougher than the thin end window GM detectors although still vulnerable to sharp points such as tweezers, nails, wire and swarf.

Weaknesses

- Expensive compared to GM detectors.
- Requires a better stabilised higher voltage supply, typically 1.6 to 2 kV.

On rare occasions can fade away slowly as a consequence of an undetectable leak.

Check for

- An acceptable performance at the minimum energy of interest. Generally they are suitable down to 0.17 MeV, in spite of the generally thicker window when compared to GM detectors.
- A good fine etched mesh grille. Detector repair costs are high, generally around £500. It makes sense to have a grille offering a high level of protection provided the response is still adequate.

C18 Thin windowed scintillation detectors

These use either a thin layer of an organic scintillator deposited on a clear plastic plate or a thin plate made from a plastic scintillator. The former variety has a generally better low energy performance. The scintillator is protected by a thin aluminised melinex window with a mass per unit area of around 1 mg cm^{-2}. Window areas range from 20 to 600 cm^2 and come in a variety of shapes, round, square or rectangular. The scinitillator is viewed by a photomultiplier which turns the light generated by the scintillator into an electric current. This can be mounted with its axis normal to the plane of the scintillator or at any angle down to the point where the axis is parallel to the plane of the scintillator. Each shape and photomultiplier tube arrangement has its merits.

Good points

- Generally very good response over a wide energy range.
- Large variety of sizes, shapes and geometries.
- A much lower response to x, gamma radiation below 300 keV than similar sized GM or proportional counters.
- Audio output always available.
- Window repairs are easy.

Weaknesses

- The operating voltage is variable, even within one type of probe.
- Susceptible to window damage, although repair is easy and cheap. This can lead to an erratic performance as a result of light getting into the detector. Rugged versions are available but are much more expensive.
- Susceptible to strong magnetic fields.

Check for

- Detectors with excessively patched foils. Normally one or two small particles over window damage are acceptable.
- Poor uniformity of response over the area of the detector caused by poor light collection or scintillator deterioration.
- Correct operating potential. Normally this should be set just below the point at which the background starts to climb. This will maximise the response to low energy and dirty sources.

C19 Spherical 210 mm diameter moderator, BF_3 proportional counter

Good points

- Lighter than most cylindrical moderators.
- Good gamma rejection.

Weaknesses

- Poor energy response compared to larger moderators, with a rapid fall-off at the high energy end, where many common sources, such as $^{241}Am + {}^{7}Be$, are encountered.
- BF_3 is poisonous.

Check for

- Suitable time constants. Switched time constants and/or an audio output help locate areas of high dose equivalent rate.

C20 Spherical 210 mm diameter moderator, ^{3}He counter

Good points

- Lighter than most cylindrical moderators.
- Non-poisonous gas.
- Lower operating voltage.

Weaknesses

- Poor energy response compared to larger moderators, with a rapid fall-off at the high energy end where many common sources are encountered.
- Poorer gamma rejection than the BF_3 detector variety. These may start to respond to gamma radiation from about 20 mSv h^{-1} upwards.

Check for

- As above.

C21 Spherical 210 mm diameter moderator, LiI(Eu) scintillator

Good points

- Lighter than most cylindrical moderators.
- Lower operating voltage.

Weaknesses

- As above, plus a much larger range of operating voltages between individual instruments.

Check for

- As above.

C22 Cylindrical moderator (≈215 mm diameter, ≈250 mm long) moderator, BF_3 proportional counter

Good points

- The best energy response of commonly available types.
- Good gamma rejection.

Weaknesses

- Unpleasantly heavy, to the point at which they may be too heavy to be carried by one person without breaching manual handling regulations.
- BF_3 is poisonous.

Check for

- As above. Many of these instruments have pulse output sockets which can be connected to external scaler-timers. This allows very long integration times to give good precision at low (site perimeter) dose equivalent rates.