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Best practice guidance for site characterisation

A report from the SAFEGROUNDS Learning Network

Managing contaminated land on nuclear-licensed and defence sites

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Best practice guidance for site characterisation. Managing contaminated land on nuclear-licensed and defence sites

A report from the SAFEGROUNDS Learning Network

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Reader interest	**Classification**	
Principally liability holders, regulators, consultants and contractors.	AVAILABILITY	Unrestricted
	CONTENT	Guidance document
The document is also intended to be accessible to other stakeholders, such as local authorities, central government and developers of potentially or actually contaminated sites.	STATUS	Committee-guided
	USER	Site owners, site contractors, regulators, developers

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6 Characterisation methods

Box 6.1 Aims of section 6

This section describes the principal techniques for characterising contaminated land on nuclear-licensed sites and defence sites. Many of the techniques, such as the use of geophysics and the construction of intrusive sampling points, are already described in existing contaminated land guidance. It is not the intention of this section to reproduce this existing guidance in detail. Only a summary is presented; the reader is signposted to existing guidance for further information. Instead, the focus is on describing those characterisation techniques that are specific to the investigation of radioactively contaminated land, and to highlight specific issues in the application of widely-used characterisation techniques to nuclear-licensed and defence sites.

6.1 NON-INTRUSIVE RADIOLOGICAL SURVEYS

Ionising radiations (in particular, gamma radiation) can be detected in the field in real time using hand-held instruments. In contrast, most chemical contaminants can only be detected at some later time through laboratory measurement. As a consequence, non-intrusive radiation surveys (or "radiological surveys") are a key component of any investigation on a potentially radioactively contaminated site. At present, there are no routinely used counterparts for detecting chemical contamination (with the possible exception of the use of gas monitoring equipment).

Radiological surveys, as with the other characterisation methods described in this section, should only be carried out by organisations experienced in undertaking such work. The guidance given below is not a method statement for carrying out a radiological survey, but a set of pointers to highlight important issues and good practice and to identify some common problems and mistakes.

The discussion is summarised from two references, which provide extensive information on the subject:

- MARSSIM – the USEPA *Multi-agency radiation survey and site investigation manual* (USEPA, 1997)
- Environment Agency R&D Technical Report – *Technical support material for the regulation of radioactively contaminated land* (Environment Agency, 1999a).

Radiological surveys in the field can be broadly divided into two types: the scanning survey and direct (or point) measurements (USEPA, 1997).

The scanning survey. Scanning radiation surveys (sometimes called walkover radiation surveys, because they are typically undertaken on foot) are carried out using portable radiation detection equipment that responds rapidly to the presence of primarily gamma-emitting radionuclide contamination on or close to the ground surface. The aim of these surveys is to identify rapidly the areal distribution of contamination at a site in order to focus further investigations. The results of the survey are generally presented in terms of counts per second and give an indication of the relative levels of radioactivity across the site.

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Direct (point) measurements. Direct measurements are carried out on the site to determine absolute values for certain parameters or to provide a better understanding of which radionuclides are present. Direct measurements tend to use instrumentation that is slower to respond or bulkier than that used for scanning surveys.

In general, a scanning radiological survey is carried out first, followed by point measurements (if necessary) in areas of interest highlighted during the scanning survey.

It should be noted that surveys in which data are recorded as equivalent dose (in, for example, $\mu Svhr^{-1}$) may be directly compared with other surveys. In contrast, surveys in which data are recorded as counts per second are not directly comparable with each other unless the same instrument has been used.

6.1.1 Design of the radiological survey

The first stage of designing the radiological survey is to identify the objectives of the work. In most cases, this will consist of one or more of the following:

- to determine if radionuclides on the site present a hazard to site personnel
- to determine the areal distribution of radionuclides on the site
- to determine the degree of heterogeneity in the distribution of any contamination
- to determine the fingerprint of the radionuclides on the site.

Having identified the objectives, the information in Box 6.2 should be used to design the survey.

Box 6.2 Design issues for radiation surveys

Which radionuclides are likely to be present on the site?	• based on the desk study (previous site usage, records of radionuclide use, environmental monitoring etc) • important because it is the primary driver in the selection of radiological monitoring equipment.
What are the natural background levels of radioactivity at the site?	• from previous monitoring data from the area. If inadequate background information exists, it will be necessary to make measurements to assess this.
What are the detection limits required for the radionuclides of interest?	• based on the derived concentration guideline levels for the radionuclides of interest, SoLA EO or background • if the radionuclide fingerprint is known, it may be possible to infer the presence of a radionuclide by measuring the most-easily detectable radionuclide in the fingerprint.
What is the size of the area to be surveyed?	• the entire area of ground that has the potential to be contaminated (or a sub-set of it)? • important because this will drive selection of the transportation used during surveying and may impact on the grid size selected.
What are the time/cost limitations on the job?	• financial and time constraints will often have a significant impact on the type of survey selected.

The detailed survey design and equipment selection will depend on the site conditions and the radionuclides expected to be present. In general, three aspects will be

considered; the type of radiation detector, its method of use and the scale of the survey grid, see Box 6.3.

Box 6.3 Key aspects of radiological surveys

Determination of the type of radiological monitoring instrument to be used (see section 6.1.2)	• based upon the expected radionuclides present, the required detection limits and cost/time constraints.
Design of the survey grid (see section 6.1.4).	• based on the size of the area to be surveyed and the size of the anomalies expected to be present • includes focused surveying of known or suspected problem areas
Determination of the most effective method of transporting the radiological monitoring equipment during the survey (see section 6.1.5).	• based upon grid size, equipment to be used and the availability of equipment • overflying restrictions may apply for some nuclear-licensed sites and defence sites – this should be clarified with the site owner

A conventional design for a radiological survey is presented in Box 6.4. However, recent developments in global positioning system (GPS) technology and electronic data capture have led to surveys being conducted in which the site is not gridded. Instead, data on both location (from the GPS) and radiological measurement are directly stored in a data-logger and the data are subsequently displayed using GIS. An example of a radiological survey conducted suing such a technique is presented in Figure 6.1.

Box 6.4 A conventional design of radiological survey

A conventional design of a scanning radiological walkover survey may consist of:

- the gridding of a site at a 5 m spacing
- a surveyor slowly walking over the whole of each grid square swinging a gamma or beta/gamma monitor a few centimetres above ground
- recording the locations and magnitude of elevated radioactivity readings by hand in a notebook
- spray-marking the ground at locations of elevated radioactivity measurements
- further investigation of suspect areas by swabbing for alpha or beta activity.

6.1.2 Instrumentation

Types of instrument

A wide range of instruments is available for the detection of radioactivity. It is outside of the scope of this guidance to give a detailed description of each instrument available; however, reviews of many types of instrument are presented in the literature (USEPA, 1997; Environment Agency, 1999a). Figure 6.2 shows a range of radiological monitoring equipment. A competent person, such as a Radiological Protection Adviser, should select appropriate radiation detectors. Instruments should be used by suitably qualified and experienced staff (such as a health physics surveyor, or Radiation Protection Supervisor) who are capable of carrying out the survey whilst adhering to the appropriate quality control and health and safety rules.

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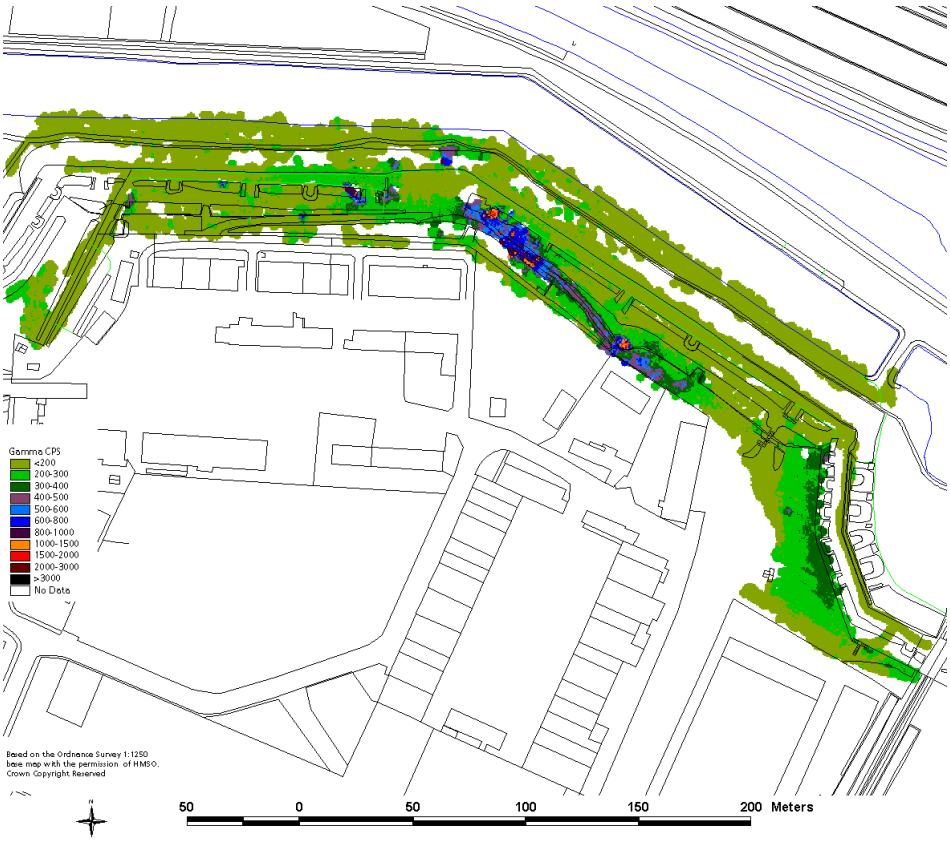

Figure 6.1 The output produced from a radiological survey that uses GPS to locate measurement positions

The selected instrumentation should be appropriate to obtain the data required. Different radiation detectors will be required to detect different types of radioactivity (alpha, beta and gamma). However, in most cases field radiological surveys focus on detection of gamma-emitting radionuclides and, to some extent, of high-energy beta emitters. This is primarily because these are the most penetrating radiations and are easily detectable at distances of tens of centimetres to metres from the ground surface (see Table 2.1). Identification of alpha emitters or low-energy beta and gamma-emitters is generally not possible during an on-site radiological survey of a contaminated site (see Box 6.5).

Box 6.5 Difficulties in detecting alpha radiation and low-energy beta and gamma radiation

There are certain radionuclides which, because of the types, energies and abundances of their radiations, cannot be detected to appropriate detection limits using field monitoring equipment. Examples include low-energy gamma emitters such as Fe-55 and low-energy beta emitter such as H-3. In addition, it is generally not possible to detect alpha-emitters on rough or wet surfaces because of their extremely low penetration (see Table 2.1). This being the case, the use of alpha detectors for walkover surveys of contaminated land sites (where inevitably the soil surface is rough and damp) is not recommended.

In many cases, a suite of associated radionuclides may be present on a site. This may either be due to the processes carried out at the site or the fact that a decay chain may be present. In these cases, it is possible to look for more easily detectable radionuclides associated with the poorly detectable alpha and low-energy beta- and gamma-emitters.

If radionuclides that are not detectable in the field are believed to be present and are not thought to be associated with detectable radionuclides, sampling and laboratory analysis will be required.

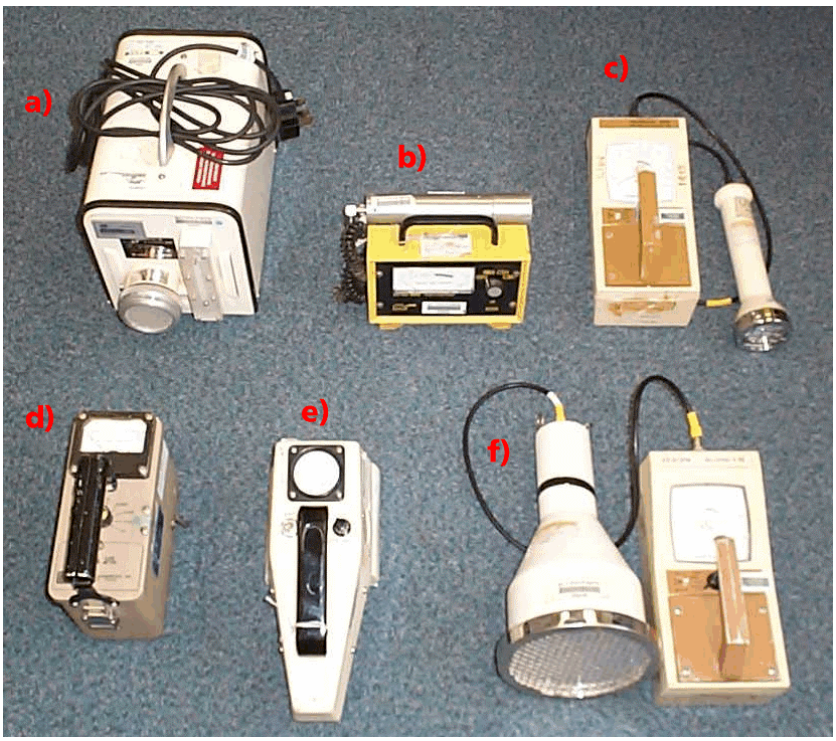

Figure 6.2 Examples of radiological monitoring equipment

a) dust monitor
b) mini instruments 5-40 end window Geiger counter
c) BP4 beta/gamma scintillation detector
d) Ludlam low-level dose meter
e) Pam 2 alpha scintillation monitor
f) 1667 beta/gamma scintillation monitor.

There are two main types of radiation detector used for most field radiological surveys. These are:

- gas-filled detectors
- scintillation detectors.

Other radiation detection methods exist (solid state detectors and passive integrating detectors). However, these are not generally used in radiological surveys and hence are not discussed further here.

Gas-filled detectors. Radiation ionises the gas within the tube or chamber in the detector. The ions travel to the electrodes, producing a signal, which is amplified by electronics (see AEA Technology (1998) for details). Common gas-filled detectors include the Geiger-Muller tube and ion chambers, the main characteristics of which are as follows.

Geiger-Muller tubes (example: Mini EP15 alpha and beta contamination meter):

- response is dependent on the energy of the radiation being detected (ie they may give a different reading for the same amount of radioactivity from different radionuclides)
- cannot tell the difference between alpha, beta or gamma radiation
- may sometimes under-read in high activity areas (due to the dead time between counts).

Ion chambers (example: Eberline RO-2, x-ray and gamma dose rate meter)

- a good response to gamma radiation over a large energy range
- do not easily detect narrow beams of radiation (chamber must be filled with radiation)
- long response time.

Scintillation detectors. Radiation interacts with certain materials, causing them to emit light. A photomultiplier tube captures the photons emitted by these materials. The electrical signal is proportional to the light output, which is, under the right conditions, proportional to the energy of the radiation hitting the scintillant (see AEA Technology (1998) for details). Common scintillants are:

- NaI(Tl) used in sodium iodide gamma detectors
- ZnS(Ag) used in alpha detectors.

Choice of instrumentation

Many different instruments are available for radioactivity surveys. Most of these are based upon the detection techniques given above. However, each instrument will be designed to monitor for particular radioactivity types or energies. In addition, each instrument will have limitations to its use or may be interfered with by other radiations.

Some of the criteria on which selection of appropriate monitoring equipment should be made are listed below:

- the type of radioactivity present ($\alpha\beta\gamma$)
- the limits of detection required
- the potential for interference
- size/weight of equipment.

Detailed descriptions of some of the advantages and disadvantages of different radioactivity monitors are provided in USEPA (1997) and Environment Agency (1999a). The selection of the most appropriate and cost-effective instrument to use for a scanning survey should be made by an appropriately experienced person.

Point measurements

The most common point measurements made during the characterisation of potentially radioactively contaminated sites are:

- dose measurements
- gamma spectrometry measurements
- alpha measurements.

These measurements are generally not carried out during scanning surveys because the response time of the equipment is often too slow.

Dose measurements are usually made at 1 m elevation (the elevation of the approximate centre of mass for a standing person) and provide a direct measurement of the dose being received at the location. Dose measurements are made to:

- ensure that site personnel are not exposed to unacceptable levels of radioactivity
- comply with the Ionising Radiations Regulations (1999).

Gamma spectrometry measurements are used to provide on-site identification of the type and radioactivity of gamma-emitting radionuclides. This technique is useful because it can:

- limit the number of samples that need to be sent for laboratory analysis
- be used to infer the presence of radionuclides that are difficult to monitor for in the field (eg the presence of the gamma-emitter 241Am may indicate that 241Pu, the beta-emitting parent, is present)
- provide valuable additional information on sites where the radionuclide fingerprint varies spatially
- provide some discrimination between surface and buried contamination (through analysis of spectra)
- be used to determine how samples need to be packaged in order to comply with the Radioactive Materials Road Transport Regulations (see section 7.2).

Gamma spectrometry measures the gamma flux at the position at the detector. To convert this flux into activity per unit volume of contaminated medium (eg Bq/g of soil), it is necessary to define:

- the detector-source geometry (eg a point source or a laterally extensive plane detector in contact with the contaminated medium or some distance from it)
- the distribution of radioactivity in the contaminated medium (eg uniformly distributed or as a thin layer on the surface)
- the radiation attenuation characteristics of the medium.

The conversion from gamma flux to activity per unit volume is undertaken using modelling. There may be uncertainty in the calculated activity per unit volume, because of uncertainty in the input parameters listed above. If this is the case, some limited sampling and laboratory analysis should be undertaken to confirm the quantitative results from the in-situ measurements.

Two main types of portable gamma spectrometer are available. These are sodium iodide- or caesium iodide-based spectrometers and semiconductor spectrometers. Sodium iodide detectors are generally handheld units that are fairly robust, but with limited spectrometric ability. Semi-conductor detectors have a greater ability to distinguish between close gamma energies, but are less robust and significantly heavier (due to the cooling unit required) than sodium iodide detectors.

Alpha monitoring should be carried out by collecting a swab of sample on a piece of filter paper or other appropriate material and (if damp) allowing this to dry. The swab samples is then held against an alpha monitor to determine if alpha activity is present. (The thin smear of material minimises shielding of the alpha particles.) This technique is for screening purposes only. If detailed information on alpha activities is required, samples must be collected for laboratory analysis. Direct overlay of the alpha monitor on the ground surface is not usually applicable to contaminated land investigations because dampness in the soil shields out the alpha particles. If direct overlay of an alpha monitor does detect contamination, it is likely that much higher activities are present than is indicated by the monitor reading.

6.1.3 Background radioactivity

As explained in section 5.4.7, in the case of land contaminated with artificial radionuclides, the definition of “contaminated” is land where activity levels are greater than 0.4 Bq/g above background. The protocols for establishing the background level for a site should be agreed with the regulator. Establishing the background will often involve measurements off-site.

Background for a screening (walkover) survey

The most appropriate method of determining background during a screening survey is to expand the scope of the screening survey well beyond the boundaries of the potentially contaminated area and into an area that is known (or at least assumed) not to be contaminated. The background survey should be carried out at the same frequency of measurement as the survey of the potentially contaminated area. The data from the areas outside of the area of contamination can be analysed to determine the distribution of background radioactivity (ie range, mode, mean etc). Background would be recorded in terms of the units used during the screening survey (often counts per second).

Background for a point measurement survey

For a survey in which point measurements are made, either using radioactivity monitors, or by collection of samples and analysis, a minimum of ten samples should be collected to evaluate background. Ideally a non-intrusive screening survey would have already been undertaken over both the potentially contaminated area and the background measurement area, increasing confidence that the background point measurements are appropriate. The results of the ten measurements should be compared to assess the variability in background. If a large variability occurs, further measurements should be made to increase the confidence in the range of background activity.

The total number of background point measurements made will depend to a large extent on the purpose of the site investigation. If the aim of the survey is to identify an area in which contamination occurs at activities significantly above background, few background samples would be required. However, if the aim is to characterise a site more fully, a high degree of confidence would be required in the value of background. Consequently, more measurements would be required.

6.1.4 The survey grid

The survey grid should be designed to take into account:

- the proposed measurement technique
- the size of the area to be surveyed
- the anticipated size of anomalies that may be present
- desk study information on potential sources of contamination in the area.

The majority of radiological surveys are carried out using a grid of some type. The scale of the grid should be selected to ensure that it is unlikely that features of interest will be missed, but should be compatible with the proposed survey instrumentation and with the scale of the overall survey area. The scale of the grid may vary over the site of interest, to allow for focused surveying in the areas of most interest. The statistical design of surveys is discussed in section 5.4.2.

Locating the survey positions

Radiological surveys are usually located using a grid marked out over the area of interest by conventional topographical surveying methods. More recently an alternate approach has been to use GPS measurements to locate survey positions, removing the necessity of marking out a grid on the site. Differential GPS can be used to locate measurement points to an accuracy of better than 1 m. GPS is suitable for locating measurements in open areas with a good view of the sky, but becomes less reliable

under trees or close to buildings because of satellites being obscured. Accurate location of measurements made during a survey is important for a number of reasons:

- to ensure that no parts of the survey area have been missed
- to allow areas of contamination to be relocated at a later date
- to allow the data to be accurately plotted and presented.

In addition, to the above locational techniques, it is also common practice to mark areas of contamination detected on-site using spray paint.

6.1.5 Transportation used during surveying

There are three main methods by which radiological monitoring equipment may be transported: by hand, in a ground-based vehicle or by air. The relative advantages and disadvantages of each approach are given below:

The walkover survey. This consists of a single person carrying up to approximately 15 kg of equipment. The walkover survey is suitable for areas up to a few hectares (both inside and outside buildings), and may be undertaken over relatively rough ground. As the equipment is carried by a single person, lightweight probes with little collimation must be used, limiting the range of radiological measurements that may be made.

The vehicle survey. This consists of a ground-based vehicle, either motorised or hand-pushed, carrying up to approximately 500 kg of equipment. The vehicle survey is suitable for large (tens of hectares), flat open areas, for example, airfields or roadways. The vehicle survey has a number of advantages over the walkover survey, which are predominantly due to the increased mass that can be carried and the fact that the vehicle is weather-proof. Sophisticated electronics may be carried that allow real-time spectrometry, multiple detectors may be employed and large-area scintillation detectors can be used to achieve low detection limits. The main disadvantage of the vehicle survey compared to the walkover survey is that the site must be flat and open.

The airborne survey (aeroplane or helicopter). This consists of an aeroplane or helicopter carrying up to approximately 500 kg of equipment. The airborne survey is a rapid method, suitable for very large (thousands of hectares), rough or inaccessible areas. However, it has the disadvantage that individual measurements will be averaged over tens to hundreds of square metres. In addition, overflying restrictions may apply on nuclear-licensed and defence sites, limiting the applicability of this technique.

6.1.6 Quality control

Instrument calibration

All radiation monitoring equipment should be routinely calibrated in accordance with manufacturer’s instructions. Before use, the following checks should be carried out:

- a battery check
- a check of the calibration date
- a function test, using a source of known activity.

Traceability (data recording and management)

The are two main methods of recording the data collected during a radiological survey. The first is the manual recording of data in a notebook. The second is direct data-capture into a data-logging device. Both methods are capable of recording good quality, traceable data, provided that appropriate quality assurance procedures are adhered to. Both methods have advantages and disadvantages in terms of the quality of data.

Advantages of manual recording of data:

- simple to record other features noted during surveying
- simple to make sketches of features.

Disadvantages of manual recording of data:

- human error possible (for example, some radiation detectors have manual switches to changes between scales; if the switch is incorrectly set, a reading an order of magnitude too high or too low could be recorded)
- data must be manually transferred from operator notebooks prior to interpretation and presentation
- difficult and/or time-consuming to process large quantities of data
- difficult to record data in poor weather conditions
- needs close supervision to prove that the area has been thoroughly monitored.

Advantages of automated data recording:

- once correctly set up, all data collection is automated and there is limited scope for human error
- large quantities of data can be collected and manipulated rapidly
- there is a full quality-assured record of all locational and radiological measurements
- data recording in poor weather conditions is possible
- data can be directly transferred to a computer for processing and presentation.

Disadvantages of automated data recording:

- possible to set up data logger incorrectly and hence record wrong or incomplete data
- more equipment to maintain and check
- data loss could occur if equipment is incorrectly used or maintained
- operator requires more training in order to use the equipment.

6.1.7 Limitations

Non-intrusive radiological surveys are limited in their applicability by three main issues:

- the type of radionuclides present – in general a non-intrusive survey can only detect high-energy beta and gamma emissions
- the depth of burial/shielding of the radioactivity – a relatively thin layer of soil may shield radioactivity from a detector
- “shine” from nearby buildings/facilities – non-intrusive radioactivity surveys will not be applicable if nearby buildings or facilities are giving rise to elevated levels of radiation in an area that is being surveyed for radioactive contamination. In this case, either increased shielding on the detector would be required (with consequent weight increase) or samples would have to be removed to a low radiation area for monitoring or analysis.

6.1.8 Common mistakes

The most common mistake made during the interpretation of radiological survey data is to assume that if the survey does not highlight any areas of elevated radioactivity, the site is “clean”. However, the shielding afforded by the soil can significantly attenuate all types of radioactivity, including gamma activity. The ability to detect buried radioactivity will depend on the type of detector used, the type and specific activity of the buried material, the depth of burial and the quantity of the buried material. In many circumstances, gamma-emitting radionuclides buried at greater than a few tens of centimetres below ground surface cannot be detected at surface.

Another common mistake is to carry out a survey of radioactively contaminated land, but not to have made any background measurements in uncontaminated areas. Background activities must be known if a sensible determination of the extent of contamination is to be made, see section 5.4.7.

Historically, some surveys may have been undertaken using equipment that was not sensitive enough to detect very low levels of radioactivity (for example, close to the SoLA Exemption Order limits). This may have lead to the incorrect conclusion that the sites were not contaminated.

6.2 GEOPHYSICS

6.2.1 The application of geophysical techniques

Geophysical techniques provide an indirect means of characterising a site prior to any intrusive works. For contaminated land sites, geophysical methods that identify variations in the near surface structure or chemistry of the ground are required.

Many nuclear-licensed sites and defence sites have a long history of development, and it is possible that records on the exact locations of disused disposal sites, underground storage tanks and demolished buildings have been mislaid. Operational sites have many sub-surface services (including electrical supplies, water supplies, gas mains, trade waste drains, radioactive waste drains, telephone lines and fibre-optic cables), some of which may not be accurately located on site plans. Buried munitions may be present on defence sites and those nuclear-licensed sites that have been previously used for military purposes.

On nuclear-licensed sites and defence sites, geophysical methods have two principal uses:

- identification of sub-surface services and munitions, which may be a hazard for intrusive investigations
- characterisation of the geological structure of the site and identification of potential waste disposal pits or sub-surface structures (such as buried tanks or foundations).

A geophysical survey will not necessarily identify all features associated with the contaminated land, or all services or munitions in an area. Safe excavation practices must be employed during the intrusive phases of the work (refer to section 6.3.1 for information on procedures for undertaking excavations and avoiding services).

6.2.2 Commonly used geophysical techniques

The three methods that are of most use for the investigation of potentially contaminated land on nuclear-licensed sites and defence sites are:

- electrical methods
- magnetic methods
- ground penetrating radar (GPR).

These techniques provide characterisation of the near-surface environment, typically within 3 m of ground surface. Other techniques, such as seismic reflection/refraction and gravitational surveys, provide information on the deeper structure at the site. These techniques are less likely to be used in contaminated land investigations and are not discussed further here.

Features that can be identified by the geophysical techniques discussed below include:

- buried objects (in particular concrete and metallic wastes)
- areas of disturbed ground (such as waste disposal pits)
- services (in particular metallic pipes or electrical supplies).

Also, but less reliably, variations in geology, plumes of contamination and groundwater saturation may be detected.

Electrical methods are divided into two types: electromagnetic surveying and resistivity profiling.

Electromagnetic surveying uses electromagnetic induction to measure the sub-surface electrical properties. Electromagnetic surveys generally produce an areal plot of apparent resistivity over the area surveyed and can be configured to look, with limited resolution, at different depths. These surveys can often identify buried objects (such as concrete foundations), disturbed ground and metallic services. They are significantly affected by surface metallic structures and care is needed to avoid anomalous readings adjacent to features such as fences.

Resistivity profiling is carried out by inserting an array of electrodes into the ground surface, passing electrical current through pairs of these electrodes and measuring electrical potential between other pairs. Interpretation of the results gives a depth profile or, using imaging methods, a cross-section of ground resistivity. Resistivity profiling is employed where resistivity data of good vertical and horizontal definition are required or where above-ground metallic objects reduce the effectiveness of electromagnetic methods. Resistivity profiling may detect buried metallic objects and changes in ground conductivity.

Magnetic methods are used to map variations in the earth's local magnetic field caused by ferrous objects. Magnetic methods are primarily used to detect buried metallic objects such as cables, drums, pipes or waste materials. They can sometimes also be used to locate areas of fill material. Magnetic surveys can be used to estimate both the depth and mass of an object. The resolution of the method decreases with depth. Surface metallic objects may affect the results of magnetic surveys.

Ground penetrating radar (GPR) systems transmit pulses of electromagnetic energy at microwave frequencies into the ground and measure the amplitude and travel time of the returned signals. The systems are used to detect buried ferrous and non-ferrous objects including plastic pipes, void spaces, drums and concrete. The penetration depth

of the electromagnetic radiation, and hence the maximum detection depth for buried objects, depends on the electrical properties of the soil.

6.2.3 Selection of geophysical methods

The geophysical survey design will depend both on the survey objectives and the site and ground conditions. In most cases, a specialist geophysical consultant should be employed to carry out the geophysical survey and to provide input into its design. As a guideline, a list of typical survey objectives and some appropriate geophysical techniques are listed in Box 6.7 below.

Box 6.7 Typical objectives of geophysical surveys and illustrative techniques to provide the required data

Objective	Proposed technique
Locate services (note: no technique will guarantee to detect all services. Safe digging practices must be used if services may be present)	• electromagnetic profiling (both in-phase and out-of-phase components) on a 2 × 1 m grid across all accessible areas of the site to detect metallic services and cables • targeted GPR on a 2 × 1 m grid to detect the most significant plastic and ceramic services (such as gas services) • Cable avoidance tool (CAT) and signal generator, to be used at all proposed excavation positions to confirm absence of services.
Detection of buried pits	• electromagnetic profiling on a 2 × 1 m grid across all accessible areas of the site.
Locate underground structures (eg building foundations)	• electromagnetic profiling using on a 2 × 1 m grid across all accessible areas of the site • ground penetrating radar (GPR) targeted into the areas of interest.
Locate non-ferrous and ferrous metal items that could relate to buried munitions	• electromagnetic profiling on a 2 × 1 m grid across all accessible areas of the site • metal detector survey at sampling locations.

Guidance on use of geophysical techniques for groundwater pollution studies is given in Environment Agency (2000).

6.2.4 Drains surveys

Drains and sediments within them may be radioactively and/or chemically contaminated. Further, leaks from drains are a potential source of contamination of the surrounding ground. The current and past uses of drains on a site should be determined in order to identify those drains that may have been used to carry chemically or radioactively contaminated liquids. In addition, historical incidents or past practice on a site may have resulted in contamination of drains that were not designated to carry contaminated effluents. The desk study (see section 5.3.2.1) should be designed to obtain such information.

Drain surveys comprise of:

- radiological surveying of selected manhole chambers and the collection and analysis of drain sediments

- surveying of drain runs using in-drain devices
- closed-circuit television (CCTV) can be used to identify breaks in the drains
- radiological surveying (typically total gamma probes) can be used to identify areas of increased levels of radioactivity.

Various in-drain devices can be used for drains surveys. Remotely operated vehicles (ROVs) are suitable for larger diameter drains; probes manually pushed along the drain using rods are used for smaller-diameter drains.

Some issues that should be considered when designing drain surveys are listed below.

- sediment build-up in drain runs may prevent deployment of in-drain devices. There may be a requirement for washing down the drains prior to the survey. Facilities should be available to handle, and if necessary treat, the sediments washed out during this process
- the impact of continued use of the drains after the survey should be considered (in particular, the impact of connections to drains outside the survey area should be established)
- calibration of in-drain gamma devices is not straightforward, and depends on the size of the drain and the distribution of any radioactive contamination. The confidence in the quantification of radioactive contamination should be established. If necessary, in-situ sampling may be undertaken using in-drain devices.

The results from the drains survey should be used to determine (i) whether the drains and sediments within them are radioactive substances, as defined under RSA, 1993 and (ii) whether drains may be sources of contamination of the surrounding ground. In the latter case, targeted sampling of the ground along the drain run should be undertaken using trial pits or boreholes.

6.3 INTRUSIVE INVESTIGATIONS

Intrusive investigations are carried out to characterise sub-surface materials in order to obtain information on contaminant distribution and on the geological and hydrogeological environment. In addition, sub-surface investigations may be used to collect samples for geotechnical testing. Geotechnical sampling and testing is beyond the scope of this guidance document. However, limited mention is made later in this section.

Intrusive investigations divide into three main aspects:

- health and safety
- techniques
- sample collection.

Many of the health and safety issues have been covered in previous sections. However, the issue of safe digging practices is an important one that is best covered here. Both intrusive investigation techniques and sample collection methods have been fully described in many other guidance documents (BS5930; British Standards Institution, 1999b; CIRIA, 1995; Scottish Enterprise, 1994). An overview of these issues, with particular reference to features of nuclear-licensed sites and defence sites, is given in the next section.

6.3.1 Safe digging practices

Safe digging on a nuclear-licensed site or defence site has three main aspects associated with it:

- avoidance of underground services
- avoidance of buried munitions
- radiological monitoring to protect workers and minimise the spread of contamination.

The avoidance of underground services and munitions are discussed below. Radiological monitoring issues during intrusive investigations are discussed in section 3.6. In addition to these aspects, hazards appropriate to working on a conventionally contaminated site must also be considered (for example, civil engineering risks and protection against chemical contamination).

Underground services

Safe digging practices should be used during the intrusive investigation, as described in the HSE document *Avoiding danger from underground services* (Health and Safety Executive, 1988). Underground services typically present the greatest hazard during the intrusive phase of a site investigation. Because of this, the general process for determining if it is safe to excavate is repeated below:

- collect and review service plans of the area in which the works are to be undertaken (either from the site owners/occupiers or from appropriate utility companies)
- identify the positions of all services using non-intrusive techniques (geophysical surveys, a cable avoidance tool (CAT) and signal generator and tracing of services between visible features such as manhole covers)
- if a planned excavation is close to the location of services, consider relocating it (provided the location is not critical to the site investigation)
- if excavating close to the position of a suspected service dig carefully by hand
- excavate carefully and stop should anything unusual be discovered.

It should be noted that:

- service plans may be inaccurate
- not all services may be shown on the service plans.

Nuclear-licensed sites will generally have site procedures for excavations, which **must** be followed. A typical procedure for undertaking excavations at a nuclear-licensed site is given in Box 6.8.

The quality of service plans for land outside the main security fence of a nuclear-licensed site or defence site may be poorer than those for services within the site. If excavating in public access areas owned by a nuclear-licensed or defence site, it is recommended that the main utilities providers for the region be contacted to ensure that their service location plans are in agreement with the site plans.

Buried munitions

Buried munitions may be present on both nuclear-licensed sites and defence sites. If the desk study has indicated that munitions could be a potential hazard at a site, a procedure must be put into place to ensure that drilling into such objects does not occur. It is recommended that site-specific advice be sought from a specialist munitions adviser.

Box 6.8 A typical procedure for undertaking excavations at a nuclear-licensed site

1. Production of a plan showing the areas of proposed excavations.
2. Production of services plans of the areas by the licensee.
3. Selection of proposed excavation positions by the contractor, taking into account the service plans. Agreement of this plan with the licensee.
4. Cable avoidance tool survey of the proposed excavation positions by the contractor. If the proposed excavation positions are free of services, positions are marked out using spray paint (ie avoid penetrating the ground at this stage). If services are found to be present, alternative positions are agreed with the licensee.
5. Confirmation by the licensee that the excavation positions marked on the ground correspond with the proposed positions, and that the cable avoidance tool survey has be completed.
6. Production of excavation permit by the licensee. The excavation permit would typically include a second set of services drawings and approvals from all interested parties (health physicists, appropriate buildings managers, ATO holders etc.) for the excavations to proceed.
7. Issue and signing off of excavation permit by the licensee.
8. Issue and signing off of permit to work by the licensee's project manager.

Notes

In addition to the procedure listed above, a cable avoidance tool should be on site and used regularly during the excavations by a suitably qualified and experienced person (SQEP).

Should any excavation need to be relocated, this entire procedure would need to be repeated for the new location. However, the permits would only require modification rather than re-issue.

Approvals are required from interested parties such as health physicists so that, if necessary, special instructions can be given on issues such as radiological hazards and monitoring requirements.

The following are some of the objects that could potentially be discovered:

- small arms ammunition rounds are typically non-ferrous and have a major dimension of around 50 mm. Although these may be present, they present a low hazard if found
- anti-aircraft shells, hand grenades, mortar bombs and thunderflashes containing high explosive and/or phosphorus. These have a typical major dimension of at least 100 mm and contain ferrous parts. These would present a hazard if found or disturbed
- bombs are typically upwards of 500 mm in dimension and most contain ferrous components (aluminium casings are a potential problem). Shells can also have dimensions greater than 500 mm. Bombs and shells could be extremely hazardous if found or disturbed.

During site characterisation, the greatest hazard could arise from drilling into the soil and encountering a shell or bomb. In this circumstance, the obstruction to drilling may not be identified and drilling may continue on the assumption that a piece of concrete has been encountered. The hazard is decreased by trial pitting on such sites, because munitions could be rapidly identified and works stopped. A procedure for investigating a site containing munitions is given below.

1. Undertake a desk study of the area to evaluate the potential for munitions to be present. If the desk study indicates a high potential for munitions to be present it is advisable to consult a specialist munitions adviser. The results of the desk study would be unlikely to change the overall characterisation approach. However, if

there is a high risk that munitions may be present, greater care should be taken during the excavation process.

2. Undertake a geophysical survey across the site to identify the positions of buried metallic (ferrous) objects. Appropriate geophysical techniques for detecting buried metallic objects are described in section 6.2. However, advice from a specialist geophysical contractor should be sought in order that the most appropriate geophysical technique for the site is employed. The geophysical survey should produce a map showing the locations of buried metallic objects.

3. The results of the geophysical survey can be used either to plan the site characterisation so as to avoid all areas with buried metallic objects, or to ensure that, if excavation must be undertaken in the vicinity of buried metallic objects, the appropriate level of caution is exercised. In the majority of cases, buried metallic objects will not be munitions.

4. Excavation to identify buried metallic object should be undertaken with care. Borehole drilling methods are not appropriate. An appropriate method would be to use an excavator to carefully remove approximately 20 cm thick layers of soil to expose the metallic object(s). A banksman should be present to observe the excavation and determine if the object has been located. This method of approach should allow munitions to be identified at an early stage, prior to them being significantly disturbed or punctured. If munitions or objects that may be munitions are discovered on nuclear-licensed sites, the site police must be informed. The site police will then involve the appropriate civilian and military authorities. It should be noted that the civilian authorities will make the occurrence public, and media interest may result. The licensee should inform the NII if buried munitions are subsequently found. Where potential munitions are located on MoD sites, the contractor must report the find to the MoD on-site contact, who will call in the appropriate assistance.

6.3.2 Radiological monitoring during intrusive investigations

Radiological monitoring is undertaken during intrusive investigations for three purposes:

- to protect the health and safety of workers
- to minimise the spread of contamination
- to provide environmental data.

Radiological monitoring should be undertaken during all intrusive investigations where radioactive contamination may be present. In the context of this guidance, this means that radiological monitoring should be undertaken during all site investigations.

An appropriate monitoring regime for an intrusive investigation is given below.

Selection of appropriate monitoring equipment:

- this should be determined by an appropriately trained person, such as the RPA
- monitors should be selected to detect the radionuclides expected to be present on the site
- monitors should be sensitive enough to ensure the safety of site workers, to enable on-site screening and selection of samples and to enable waste segregation (if required).

Monitoring of the ground surface prior to excavation at that location:

- this should be carried out in addition to any previous radiological surveying works over the area, to ensure that the extent of the surface radioactive contamination is known.

Regular monitoring of the excavation:

- in trial pits, a probe can be lowered into the excavation to detect if radioactivity is present. This provides a sensitive measure of the first occurrence of radioactive contamination, which is detected before the contaminated material is excavated. (Note that the background level of radioactivity detected during excavation will alter as the excavation becomes deeper, because of geometrical effects and because different soil horizons are encountered)
- in temporary shallow boreholes used for soil sampling, an appropriate narrow-diameter probe would be required for down-hole measurement. Although this would provide useful depth-dependent information with better sensitivity than could be achieved from monitoring spoil or samples, it is limited by issues such as borehole stability. Down-hole radiological monitoring is discussed further in section 6.3.4. As with monitoring of trial pits, the background level of radioactivity may alter with depth because different soil horizons are encountered.

Regular monitoring of the spoil generated during the excavation process:

- this will ensure that any buried radioactive contamination will be detected in the spoil produced by the excavation process
- the spoil should be monitored at regular intervals, and any changes in radiological contamination should be noted.

Regular monitoring of soils to aid in the sample selection process:

- see section 6.3.4.

Monitoring on completion of each excavation:

- personnel should be monitored to ensure that they have not been contaminated with radioactivity
- the ground surface should be monitored to ensure that it has not been contaminated with radioactivity
- the excavation equipment should be monitored to determine if it has become contaminated with radioactivity (in which case decontamination will be required, in addition to any routine cleaning procedures taken to minimise cross-contamination)
- the outside of the sample containers should be monitored to ensure that (i) there is no loose surface radioactive contamination and (ii) any external radiation levels do not present a hazard to personnel.

Monitoring on completion of the intrusive phase of the site investigation:

- all equipment used in the investigation should be monitored and a radiological clearance certificate issued by the relevant Health Physicist
- all samples should be monitored and issued with the appropriate documentation (eg a radiological clearance certificate for uncontaminated samples) prior to being transported to the laboratory.

6.3.3 Types of intrusive investigation

Samples collected during the site characterisation will be of the following types: soils and rocks; surface waters and groundwaters; soil gases. Soil samples are collected either

manually, by hand-digging or by using an auger, or mechanically, using an excavator (for trial pits) or drilling rig (for boreholes). Groundwater samples are generally collected from boreholes that are either temporarily or permanently cased, or on occasion from trial pits. Gas samples are generally collected from temporary shallow probes or from boreholes completed as soil gas monitoring points.

6.3.4 Methods of intrusive investigation

There are several methods of excavating into the sub-surface. Many of these methods have been described in great detail in other guidance (BS5930; British Standards Institution, 1999b; CIRIA, 1995; Scottish Enterprise, 1994). An outline of the methods that are applicable to nuclear-licensed sites and defence sites is given in Box 6.8. Particular reference is made to the specific details that make techniques more or less suitable for use on potentially radioactively contaminated sites. Of particular relevance are excavation techniques that minimise the amount of spoil generated and minimise the potential for contamination to be spread around the excavation area. All of the methods described are technically valid, but their applicability will vary depending on site conditions and on the requirements of the survey.

Because trial pits generate large quantities of spoil, their use should be minimised in areas known to be radioactively contaminated.

Field logging

It is important to log all relevant information when carrying out an intrusive investigation. Such information should consist of, as a minimum:

- location of excavation and location number
- depth of excavation
- type of excavation
- date and time of excavation
- descriptions of the soil/rock/made ground with depths
- the depths, numbers and types of samples collected
- field monitoring information (gamma monitoring, dose monitoring)
- backfilling details
- photographs taken.

An example field logging form is presented in Figure 6.3.

Minimising cross-contamination

Cross contamination of samples should be minimised by:

- selecting appropriate investigation and sampling techniques
- decontaminating equipment between sampling locations.

The main methods of minimising cross-contamination between different layers in the ground during excavation are:

- if trial pitting using an excavator, take large bucket scoops and collect soil samples from the centre of the bucket (ie the soil that has not had contact with the excavator bucket)
- if drilling, use a method that installs a temporary casing to isolate different soil layers
- if using a percussive method such as window sampling, remove the smeared layer from the outside of the core before samples are collected.

Between sampling locations, all equipment that has come directly into contact with the contaminated soil or groundwater should be cleaned. Cleaning will normally be carried out using a pressure washer or steam cleaner. The wash water from the cleaning process should be contained, tested and disposed via an appropriate route. It is good practice to sample first those areas that are expected to be least contaminated, and to work towards the most contaminated areas.

To minimise the potential for contamination to be spread, all excavation sites should be kept clean and tidy. One method of minimising the spread of contamination is to use polythene ground sheets or boards to prevent potentially contaminated spoil from mixing with uncontaminated surface soil.

Excavation type		Excavation number		Date/ time		
Location				Monitoring details		
				Beta/ Gamma (cps)	Dose (μSvhr^{-1})	Other
Depth (mbgl) From	To	Soil/ rock desciption	Sample number/ type	Probe type/ no.:	Probe type/ no:	Probe type/ no:
Further information (backfilling details, photographs taken etc.)				Logged by:		

Figure 6.3 Example field logging proforma

Backfilling with and disposal of spoil

Spoil will be generated during intrusive investigations. Small quantities will be generated by drilling boreholes; larger quantities will be generated during the excavation of trial pits. There is a potential for backfilled excavations to lead to future cross-contamination of the site (for example, by backfilling contaminated spoil at a depth beneath its current position on the site). Therefore, the approach to backfilling excavations with spoil should be agreed with the relevant environment agency before proceeding with the work.

Where contamination is detected in the field or is visible, the environment agencies will probably require that the excavated material is disposed as waste and that the excavation is backfilled with clean imported material. If contamination is not detected or seen in the field, a pragmatic approach could be to backfill excavations with spoil pending the results of laboratory analysis. This avoids the need either to create large volumes of (potentially unnecessary) waste or to leave excavations open until analysis has been completed (with the associated risks to safety).

Contingency plans should be prepared for the case where subsequent laboratory analysis indicates that radioactive wastes have been backfilled into the excavation. This could be where alpha-emitting or low energy beta-emitting radionuclides are present. When

characterising known contaminated ground, the relative volumes of waste produced is one of the issues to be considered when deciding between the use of trial pits and boreholes (see Box 6.8).

In certain circumstances, it may be necessary to replace spoil into the trial pit from which it was obtained even though it is known to be significantly contaminated. If, for example, the external doses being received from the material were excessive, the material may be returned to the trial pit (as storage rather than disposal) to reduce the immediate radiation hazard.

Backfilling with spoil is not acceptable for boreholes that penetrate an aquitard separating two aquifers; a low-permeability seal is required to prevent continued cross-flow through the borehole after it has been abandoned (Environment Agency 1999c).

Surplus drilling spoil and samples not required for analysis are waste materials and should be disposed of appropriately (see section 7 for a discussion of waste management procedures).

Radiological clearance of equipment

On completion of the site works in a potentially radioactively contaminated area, it is good practice to have all site investigation equipment radiologically monitored and a radiological clearance certificate issued. In radiologically designated areas, it will be necessary for equipment to be monitored and a clearance certificate issued before permission will be granted for the equipment to be removed from the site.

Downhole radiological measurements

Downhole radiological measurements complement non-intrusive radiological surveys (see section 6.1) and radiological monitoring during intrusive investigations (see section 6.3.2). The technique, which gives information on the distribution of radioactivity along the borehole axis, can be used in three situations:

1. In conjunction with permanent monitoring points (for example, downhole logging of groundwater monitoring boreholes).
2. During construction of conventional temporary sampling boreholes from which soil and/or water samples are being collected (see section 6.3.2).
3. In conjunction with temporary percussive holes from which no waste or samples are produced at surface (for example, cone penetrometer testing).

Downhole radiological measurements can be used to improve targeting of samples taken for subsequent laboratory analysis or to provide interpolation between sparse data from borehole samples (for example, where contamination of bedrock is focused in fractures that may be difficult to sample, or where drilling conditions lead to depth intervals where no solid material is returned to surface for sampling). In addition, the third situation, above, is useful for characterising areas where there is relatively high contamination by gamma-emitting radionuclides, because measurements can be made without the need to produce waste.

In all applications of downhole measurements, it is necessary to consider the following:

- the penetrating power of the ionising radiation in the soil or rock around the borehole, in any borehole construction materials (such as casing) and in the air or water filling the borehole. Downhole logging is most appropriate to determining the distribution of gamma-emitting radionuclides

- calibration of results. The technique provides information on the distribution of areas of elevated radioactivity. Accurate calibration to derive specific activities (eg Bq/g of soil) requires information on source-detector geometry, on the spatial distribution of the radionuclide and on the attenuation characteristics of the radiation. If quantitative information on specific activities is required, laboratory analysis of samples will be needed to build confidence in the calibration
- the susceptibility of the approach to any external contamination of the detector assembly. It is important to monitor for surface contamination on the detector at frequent intervals and to evaluate results with caution if surface contamination is detected.

It is also necessary to consider the consequence of repeated purging of groundwater monitoring boreholes on downhole radiological measurements. Purging leads to some of the fine-grained material from the formation being drawn into the filter materials placed around the well screen (if these are present) or into the borehole itself. In the latter case, the material settles to the bottom of the borehole (silting up the well). Because radioactive contamination is often concentrated on the fine-grained fraction of the soil or rock, this redistribution of material can have a significant effect on downhole radiological measurements. In the extreme case, downhole measurements may be dominated by radioactivity from contaminated silt at the bottom of the borehole. For this reason, it is best practice to undertake downhole radiological measurements prior to groundwater sampling. Where this is not possible, data from downhole radiological measurements should be interpreted with caution.

6.3.5 Sampling of soil and rock

Sample selection

Soil and rock samples are of two main types: mechanically disturbed or undisturbed. Mechanically disturbed samples are generally adequate for contamination surveys, whereas mechanically undisturbed samples are typically required for geotechnical surveys. There are three main methods of selecting soil and rock samples in the field:

- sampling from predefined depth intervals
- sampling based on visual features (ie from different geological units or different layers of made ground)
- sampling based on the results of radiological or chemical monitoring.

When excavating on a potentially contaminated site, radiation monitors may be used to identify the excavated material with the highest levels of radioactive contamination. This information can then be used to focus sampling, ensuring that at least some of the samples containing the highest levels of radioactive contamination are selected. Care should be taken to avoid over-estimating the volume of contaminated material present if only the most radioactive samples are selected for analysis.

In any survey, it is important (i) that samples are representative of ground conditions and (ii) that sufficient material is collected to enable all required analyses to be undertaken (including sufficient material for repeat analysis, should this be necessary). The sample size can be significant when undertaking radiological measurements. For example, the time taken to analyse for gamma-emitting radionuclides to a specified detection limit by gamma spectrometry is approximately inversely proportional to the weight of sample analysed. In general, it is sufficient to collect approximately 500–1000 g of sample in an appropriate container for gamma spectrometry analysis.

Box 6.9 Techniques for intrusive sampling

Technique	Outline of method	Advantages	Disadvantages
Soil gas probing	Gas sample probe inserted into soil to a depth of <0.5 m	• simple method of obtaining the areal soil gas data • no spoil generated • low potential for contamination to be spread	• only suitable for gas sampling • can only be used at shallow depth
Hand-digging	Use of trowel to collect samples to <0.5 m depth	• samples can be collected from any surface location • base of hole can be monitored during excavation • little equipment is required • low potential for contamination to be spread • low risk of damaging services • cheap	• maximum depth of sampling ~0.5 m. • disturbed samples are collected
Hand augering	Use of hand auger to drill holes in soft materials to a depth of approximately 1 m	• little equipment is required • cheap • samples can be collected in areas with poor access	• maximum depth of sampling 1 – 2 m • samples are significantly disturbed and there is a high potential for cross contamination of layers • only appropriate for fine grained soft sediments
Trial Pitting	Use of tracked or wheeled excavator to dig trial pit to <6 m depth	• large volume of soil exposed – sampling and logging more representative • observations of base of trial pit can be used to identify potential hazards • base of excavation may be monitored for services and contamination as trial pit progresses	• large quantities of potentially contaminated waste materials brought to ground surface • medium risk of damaging services (unless banksman identifies marker tape etc.) • maximum depth 6 m – note that the trial hole will often collapse when groundwater is encountered
Borehole drilling	Cable percussive drilling in soils/weak rocks	• suitable for a wide range of materials • suitable for in-situ geotechnical testing and geotechnical sampling • good definition of depth of materials • little or no use of drilling fluid • suitable for the installation of permanent groundwater or gas monitoring installations • possible to use low-head room rigs for sampling in difficult areas	• drilling process produces relatively large quantities of spoil (although less than trial-pitting) • driller's mate is closely involved with the drilling process and has a relatively high potential to become contaminated • relatively slow • maximum depth tens of metres depending on material

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Box 6.9 Techniques for intrusive sampling

Technique	Outline of method	Advantages	Disadvantages
Borehole drilling (continued)	Solid stem rotary augering in soils/ weak rocks	• relatively fast • little or no drilling fluids required • suitable for the installation of permanent groundwater or gas monitoring installations • can undertake inclined drilling for sampling under buildings etc	• high potential for cross-contamination of samples • depth resolution poor • not appropriate for coarse gravelly materials
	Hollow stem rotary augering in soils/weak rocks	• relatively fast • good quality samples • good depth definition • suitable for the installation of permanent groundwater or gas monitoring installations • can undertake inclined drilling for sampling under buildings etc	• not appropriate for coarse gravelly materials
	Rotary drilling in rock (truck- or mini-rig mounted)	• rapid drilling possible • can be used to drill through overburden using rotary-percussive drilling • maximum depth hundreds of metres • good quality core and samples • suitable for the installation of permanent groundwater or gas monitoring installations	• expensive • drilling fluids may contaminate sampled and surrounding rock • difficult to control and dispose of drilling fluids and cuttings • difficult to monitor drilling cuttings • truck-mounted rigs not suitable in restricted space areas
	Windows sampling	• small quantities of waste produced • core can be produced in clear plastic sleeves • simple to monitor cores to select samples and for health and safety purposes • relatively quick • cheap • possible to use in restricted space areas	• maximum depth usually less than 5 m • samples are usually compacted • small quantities of sample are recovered • samples are not suitable for many geotechnical tests • difficult to identify water strikes • not very reliable in granular soils

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Certain other analyses require additional field sample preparation. For example, analysis for tritium or volatile organic compounds typically require the soil or rock sample to be stored in a sealed septum vial immediately after collection, the aim being to prevent the loss of volatile compounds during transportation to the laboratory. The chemical or radiochemical analyst will provide advice on the volumes of samples required and on any field preparation required (for example, the addition of ultra-pure water).

In some cases, for example when remediation of the site is a probable outcome of the site characterisation and where a large averaging volume has been agreed with the appropriate regulator, it may be appropriate to homogenise samples from a large volume of material. For example, this approach has been used to determine the average contaminant concentrations in ~30 m^3-sized disposal pits.

Sample collection

Disturbed soil may be brought to ground surface using any of the intrusive investigation techniques listed in section 6.3.3. Disturbed samples are generally collected from the spoil produced by the excavation process, using a tool such as a stainless-steel trowel, and placed into the appropriate sample containers (as supplied or advised by the analytical testing laboratory).

It will often be necessary to characterise areas of made ground or coarse-grained soil (such as glacial till or rock fill). In this case, samples that are representative of the entirety of the ground cannot be collected because of the presence of coarse gravels, cobbles and boulders. It is neither practicable nor appropriate (given that any contamination will be concentrated within the finer-grained fraction) to analyse these coarse-grained components of the soil. In this case, the coarse-grained fraction should be discarded, and only the finer-grained fraction sent for chemical and radiochemical analysis. The approximate proportion of unsampled material should be recorded to enable the measured contaminant concentration in the finer-grained component to be corrected (ie diluted), if required, to account for the presence of the coarser fraction.

It is best practice to consider the extent of any bias introduced by analysing only the finer fractions of the soil samples. This can be achieved by grinding and homogenising soil samples (at least the sub-pebble-sized fraction), and analysing the resulting sample.

Relatively mechanically undisturbed soil samples are generally collected by using one of the standard drilling techniques (such as cable percussive drilling or coring through the centre of a hollow stem auger). The samples are usually collected using an open tube sampler, such as a U100 tube or a plastic core liner. Rotary coring is typically used to obtain mechanically undisturbed rock samples.

6.3.6 Liquid and gas sampling

Installation of permanent monitoring points

All of the borehole drilling methods described above may be used for the installation of groundwater or gas monitoring points. The key issues to consider when selecting the drilling technique are:

- confidence that the drilling technique can achieve the required depth of penetration at the required borehole diameter
- health and safety issues, such as the potential generation of airborne contamination during drilling (for example if air-flush rotary drilling is the selected technique)

- any limitations on the use of a flushing medium (eg air, foam, water), which may compromise sample quality
- environmental issues, such as spreading of contamination in the ground and control of drilling returns
- speed and cost.

Trial pits may also be used for the installation of shallow monitoring points, by carefully backfilling around the monitoring equipment. However, it should be noted that a large volume of soil would be disturbed and this may affect the results obtained during monitoring.

Details of the design, construction, installation and commissioning of permanent groundwater and gas monitoring points are beyond the scope of this guidance document. Readers should refer to the extensive guidance already available on the subject (for example, Environment Agency, 1999b; CIRIA, 1993a).

Groundwater sample collection

Groundwater sampling methodologies are described in detail in a number of other guidance documents (for example, CIRIA, 1993; Environment Agency, 1999b). An outline of the methodology is given below.

Groundwater samples are generally collected by one of two methods:

- pump sampling
- bail sampling.

The method used will depend on the feature from which the groundwater sample is being obtained (completed borehole, temporary cased borehole or trial pit) and on issues such as the amount of suspended sediment present and the permeability of the surrounding material. Usual practice is for trial pits to be bail-sampled and for boreholes to be pump-sampled.

Pump sampling is the preferred method of sampling from a borehole because a large volume of water can be withdrawn prior to collecting the sample, ensuring that the sample is representative of the groundwater in the rock mass rather than that in the borehole. It is best practice to withdraw three borehole volumes of groundwater prior to collecting samples, or to carry out in-line monitoring (for electrical conductivity, pH etc) and to sample after measurements have stabilised.

When pump-sampling a borehole on a nuclear-licensed or defence site, adequate provision should be made for disposal of the waste-water generated (see section 5.4.5). Direct disposal of radioactively contaminated water to ground, or by a surface water body, will not be possible unless covered by the site's authorisation under RSA93 (see section 7). Similarly, disposal of chemically contaminated water to ground or by a surface water body would require authorisation from the environment agency.

Radiological monitoring using standard field instruments will typically not detect contamination in water samples, because the radionuclides are typically present at much lower activity concentrations than in soil and may only emit "soft" beta or alpha radiation. Laboratory analysis of groundwater samples for radioactivity is generally required. For example, this is the case for tritium, a "soft" beta emitter, which is a common radioactive contaminant found, as tritiated water, in groundwater in the vicinity of some nuclear-licensed and defence sites, see section 6.4.4. Tritiated water is highly

mobile in soils and groundwater. Naturally occurring dissolved radon/radon daughters are also likely to be present.

The selection of suitable sample containers and preservation techniques (typically involving refrigeration or the addition of acid or alkali to prevent precipitation or degradation of the sample) is discussed in existing guidance, for example Environment Agency, 1999b, and is not considered in detail here. All groundwater samples should be filtered (typically to 0.45 µm) in the field prior to addition of the preservative. It is good practice (i) to refrigerate groundwater samples to approximately 4ºC after collection and prior to analysis, (ii) to store samples in the dark and (iii) to minimise sample storage time. This is particularly important for analysis of organic compounds, which may otherwise degrade during storage. In practice, refrigeration of large samples (around 5 litres) for radionuclide analysis is impracticable and is not necessary. An illustrative groundwater sample storage and preservation scheme is shown in Box 6.10.

Box 6.10 Illustrative scheme for storage and preservation of water samples

Determinand	Container	Preservation
All radionuclides except tritium	5 litre HDPE	50 ml HNO_3
Tritium	0.5 litre glass	None
Metals	1 litre HDPE	Hardness, HNO_3
Cyanide	0.1 litre HDPE	NaOH
Chloride, sulphate etc., alkalinity	250 ml HDPE	None
Non-volatile and semi-volatile organics	1 litre amber glass	None
Volatile organics	Glass serum vials (sealed with PTFE-faced rubber septum)	None

Sampling of non-aqueous-phase liquids

Non-aqueous-phase liquids (NAPL) divide into two types, light NAPL (LNAPL) or dense NAPL (DNAPL). These types are less dense and more dense than water respectively and hence will either sink through or float on the groundwater.

Sampling DNAPLs is extremely difficult, primarily because the probability of intersecting a pool of DNAPL in the base of an aquifer, and having the DNAPL flow into the borehole, is low. DNAPL is usually inferred to be present in an aquifer by, for example, high or increasing dissolved concentrations with depth, or from records of known disposals. The sampling of DNAPL will not be discussed further here. Further information on DNAPLs is provided elsewhere (for example, Fetter (1992)).

The sampling of LNAPL may be carried out in a number of ways, provided that the borehole is of suitable design (the screen section of the monitoring point should extend from just above to below the zone of water table fluctuation). The most common and simplest method of sampling is to bail a sample from the surface of the groundwater. The LNAPL sample should be collected before any groundwater purging, and should be carried out in such a way as not to emulsify the free product. The thickness of LNAPL in the borehole can be determined using an interface probe, although it should be noted that this will probably not reflect the thickness in the aquifer, because of capillary pressure effects.

Soil gas sampling from permanent monitoring points

The sampling of permanently installed gas monitoring points is generally used for monitoring methane production from landfilled putrescible wastes. It is unlikely that such monitoring will be required on nuclear-licensed sites or defence sites. Extensive guidance on the identification of landfill gas already exists (see for example the series of CIRIA reports on methane (CIRIA, 1992; CIRIA, 1993a; CIRIA 1993b; CIRIA 1995)) and is therefore not repeated here.

Soil gas surveying

Soil gas surveying provides information on volatile or gaseous contaminants within the near-surface soils. It is used to identify the source of volatile or gaseous contaminants (or their parents, in the case of Rn-222), such as those that may be associated with areas of contaminated land. Although soil gas surveying appears to be straightforward, there may be significant uncertainties in interpreting the data, principally due to variations in the permeability and moisture content of the ground, which affect the ability of soil gas to migrate. In addition, results are commonly influenced by meteorological factors, such as the extent of recent rainfall, barometric pressure and windspeed.

Soil gas surveying may be used as an indicator of the presence a number of contaminants, including:

- volatile organic compounds (VOCs) such as petroleum hydrocarbons or organic solvents
- organic compounds that are not VOCs, but that produce CO_2 gas during biological or chemical breakdown
- mercury
- radon (an indicator of the presence of radionuclides in the uranium and thorium decay chains).

The largest potential use of soil gas surveying on nuclear-licensed sites and defence sites will be the identification of sources of VOC contamination. Radon gas surveying may also have some potential use on these sites as the presence of radon indicates that radionuclides in the uranium or thorium decay chains are present.

Box 6.11 Soil gas surveying

Ground-probing soil gas surveys typically involve the following stages:

- determination of the sampling pattern based on the size of the site, the quantity of information required, the desk study and walkover survey information, cost implications
- insertion of the sampling probe at each location
- purging of atmospheric gases from the sampling probe
- withdrawal of soil gas sample
- analysis of the soil gas either on site using portable instruments (eg photo ionisation detector or gas chromatograph) or in the laboratory (following storage in a suitable gas tight container).

Soil gas surveying is a screening technique. Therefore, the analysis is usually completed in the field using on-site instrumentation. Areas within the highest concentration contours (“hot spots”) are targeted for more exhaustive soil sampling and analysis. More

detailed descriptions of soil gas surveying techniques are provided in guidance produced for Scottish Enterprise (1994).

Advantages of soil gas surveying are that it is a rapid screening technique which can aid in the identification of areas of chemically (or radioactively, in the case of radon) contaminated land and it is relatively inexpensive.

Limitations of soil gas surveying are that migration of soil gas may be significantly affected by the near surface geological and man-made structures. Because of this the soil gas concentration may not be proportional to the concentration of contaminant in the source area, interpretation of results may be difficult and a negative result does not necessarily indicate that there are no contaminants present.

6.3.7 Sample labelling and transport

Samples should be clearly labelled in a manner that cannot be removed during handling. The labels should include the following minimum information:

- location number
- depth interval
- date of sampling
- hazard information.

Transport of samples to the laboratory should take place as soon as possible after sample collection to minimise the potential for degradation to occur. Advice on storage conditions should be sought from the analyst.

Radioactively contaminated samples containing greater than 70 Bqg^{-1} total radioactivity become subject to the Radioactive Substances (Road Transport) Regulations. If this is the case, samples are required to be labelled, packaged and transported in accordance with the regulations. However, the total radioactivity of a sample is not known until is analysed. If it is suspected that some samples may contain greater than 70 Bqg^{-1} of radioactivity, it may be necessary to undertake on-site screening analysis, for example using a portable gamma spectrometer, to determine the appropriate method of transport. If this is not possible, then samples should be transported in accordance with the requirements of the Radioactive Substances (Road Transport) Regulations. Waste management and transport of radioactive materials is discussed further in section 7.

6.3.8 Geological logging/geotechnical testing

Geological logging

All boreholes and trial pits should be logged following BS5930:1999. In addition, the following information should be recorded:

- depth and results of any in-situ radiological or chemical monitoring
- depths and depth ranges and type of any samples collected for chemical or radiochemical analysis
- depths of any man-made features (BS5930 logging will only record such features as made ground).

Photography

Photographs provide a valuable record of a contaminated land survey. However, there are often significant restrictions to the use of cameras on nuclear-licensed sites and

defence sites. Prior to use of a camera on these sites, permission should be sought from the site operator. Ideally photographs should be taken of:

- all sampling locations
- trial pit walls
- any exposed in-situ geological materials
- cores samples prior to them being divided up for analysis.

Geotechnical testing

In some circumstances it may be possible to combine a contaminated land survey with a geotechnical survey. However, a number of points should be borne in mind:

- the quality of the contaminated land survey may be degraded if sampling locations are moved to provide the best location for geotechnical sampling (or vice versa)
- the appropriate intrusive method for the contaminated land survey may not be appropriate for the geotechnical survey (or vice versa)
- samples must be tested for contamination prior to the geotechnical testing being carried. This is required to establish any special health and safety measures that need to be undertaken. Note that any laboratory testing of radioactive substances, as defined under RSA93, will require an open source registration (see section 6.4.1) from the relevant environment agency, and notification under IRR99 if activities involved are above exemption levels.

Geotechnical testing methods are described in detail in BS1377, 1990 *Methods of test for soil for civil engineering purposes*. Some examples of common tests are given in Table 6.1.

Table 6.1 Common in-situ and ex-situ tests

In-situ tests	Ex-situ tests
standard penetration test	liquid and plastic limits tests
in-situ California bearing ratio test	moisture content
hand shear vane test	undrained triaxial compression tests
perth penetrometer test	California bearing ratio tests
	pH and sulphate testing ()

Note: Although pH and sulphate testing are chemical tests they are included in the geotechnical suite as they are used to determine the potential for degradation of foundation to occur

6.4 CHEMICAL AND RADIOCHEMICAL ANALYSIS

6.4.1 Selection of an appropriate laboratory

The laboratory chosen should be competent to undertake the required analysis. Competence is demonstrated, in a general way, by accreditation of the laboratory by NAMAS (under the auspices of the United Kingdom Accreditation Service, UKAS). It is, however, important to confirm that accreditation is held for the specific analyses required. The testing laboratory should be committed to the implementation of effective and efficient quality management systems consistent with the requirements of BS EN ISO9001, and should be able to demonstrate that adequate quality control procedures are applied.

It is desirable that the laboratory participates in external inter-laboratory comparison schemes, such as the WASP (Workplace Analysis Scheme for Proficiency) inter-

laboratory scheme run by the Health and Safety Executive, the AquaCheck scheme organised by WRc Ltd and CONTEST (CONtaminated land TESTing)organised by the Laboratory of the Government Chemist.

The sites that are being considered by this best practice guidance are potentially radioactively contaminated. Chemical contamination may also be present. When selecting an analytical testing laboratory, it is necessary to ensure that it has the required authorisations to handle the types of sample that will be sent to it.

The laboratory requires an open registration (that, is a licence to handle open radioactive sources, such as radioactively contaminated soil and water) if it is to analyse radioactive material (as defined under RSA 93) produced from a site characterisation. The regulatory authority for the registration process is the relevant environment agency. An authorisation to accumulate and dispose of waste may also be required. Notification of HSE under IRR99 will be required if the quantities of radioactive materials involved exceed specified levels.

6.4.2 Chain of custody

A chain of custody document should be prepared for each sample or batch of samples and should record collection in the field, off-site consignment to the testing laboratory and receipt by the testing laboratory. Subsequent to testing, the surplus portions of the samples may be returned to the site operator (for long-term archiving, storage or disposal) or may be disposed by the principal contractor or analytical testing laboratory in accordance with UK legislation. The chain of custody document should record these transfers. A copy of the chain of custody document should be kept in the project file.

The disposal of radioactively contaminated samples will be discussed in section 7.1.

6.4.3 Analytical testing strategy

It is not possible to analyse all samples for all possible contaminants, and a strategy is therefore needed to prioritise and sequence the chemical and radiochemical analyses undertaken. The strategy would take into account:

- the objectives of the site investigation (for example, is it to determine if a site is chemically or radioactively contaminated or to design a remediation strategy)
- the conceptual model of the site, which would identify the potential contaminants of concern (PCOCs), potential sources and mechanisms of contamination, and the potential pathways and receptors
- the available budget and timescale for the site investigation.

A phased approach is generally taken to the chemical and radiochemical testing. This is likely to involve:

on-site screening of samples, for example:

- radioactivity, using hand-held alpha and beta/gamma monitors
- volatile organic compounds (VOCs), using a photo-ionisation detector (PID) or gas chromatograph (GC).

laboratory screening techniques, for example:

- gross alpha/beta
- gamma spectrometry (which also provides detailed analysis for specific radionuclides)
- tritium

- hydrocarbon analyses (eg diesel range organics (DRO: C11-~C35) and petrol range organics (PRO: C4-C10))
- polyaromatic hydrocarbon (PAH) and polychlorinated biphenyl (PCB) screens
- beryllium.

detailed laboratory analysis, for example:

- alpha spectrometry to determine activities of uranium and plutonium isotopes
- chemical separation followed by specific radionuclide analysis (for example, 90Sr)
- trace metal analyses (eg Hg, Pb, Zn, hexavalent chromium)
- analyses to determine the potential for in-situ degradation of organic contaminants (eg presence of electron acceptors (sulphate, ammonium, nitrate and iron) and indicators of microbial degradation (CO2, methane, sulphide)
- analysis to determine presence of potential degradation products, particularly if these are more toxic than the parent material
- analysis of colloids.

In general, for all types of analyses, uncertainty in the results increases with decreasing concentration or activity of contaminant.

Note that some laboratory screening can be undertaken on site. This may be required to confirm that samples are correctly packaged and labelled for off-site transport in accordance with Radioactive Materials Road Transport Regulations (see section 7.2).

6.4.4 Analysis of radioactivity in soils and waters

The two principal analytical techniques used to detect radioactivity in soils and waters are gross alpha/beta analysis and gamma spectrometry. The application of these techniques is discussed in Boxes 6.12 and 6.13 below. The analysis of tritium in soils and waters is also discussed.

Box 6.12 Gross alpha and gross beta measurements

In principle, a gross alpha and gross beta measurement (typically referred to as “gross alpha/beta”) will be sufficient to characterise the total radioactivity of the sample. This is the case for analysis of **water samples**, where accurate and precise detection to less than 0.1 Bql^{-1} can be achieved. For comparison, these levels are below the Guideline Values produced by the World Health Organisation for radioactivity in drinking water.

In practice, however, gross alpha/beta analysis of **soil samples** is a screening technique, which enables distinction to be made between uncontaminated samples and those samples contaminated to levels of a few Bqg^{-1} or more. The intervening region is more difficult to characterise because:

- the soil sample required for analysis is very small (<1 g) and sub-sampling errors (arising from sample heterogeneity) may be significant
- the typical sample preparation technique involves using only the fine-grained (<200 μm) portion of the soil. This can introduce a systematic bias in the result, because any radioactive contamination tends to be associated with the fine fraction.

A more accurate measurement of gross alpha/beta activity in soil can be obtained if a 100 g-sized sample of soil is homogenised and crushed so that there is no size separation prior to analysis.

Gross beta analysis does not detect very weak beta-emitters such as ^{3}H, ^{14}C, ^{35}S, ^{129}I and so on. If these isotopes are potential contaminants in the soil or water sample, additional isotope-specific analysis will be required.

Tritium is common contaminant on nuclear-licensed sites. It is present as tritiated water, which behaves in a chemically identical way to naturally occurring water (H_2O). As a consequence, it is highly mobile and commonly migrates from the near-surface environment into groundwater. The extent of migration is limited by the short half-life of tritium (12.3 years). Special precautions are needed when sampling and analysing for tritium, to prevent evaporation of the sample and/or isotopic exchange with naturally occurring water. It is possible to analyse for tritium both in soil samples and in waters; in both cases, tritium is present in the aqueous phase.

Quantification of tritium contamination in the unsaturated zone generally involves analysis of soil samples. The tritium activity can be expressed either as Bq/g of soil or as Bq/L of soil porewater. The latter is more informative, because it can be directly compared with the activity concentration of tritium in the underlying groundwater. However, the moisture content of the soil sample must be measured to derive the porewater activity. In the saturated zone (ie below the water table), either soil samples or water samples can be collected and analysed. In practice, determination of tritium activities in soil or rock from beneath the groundwater table would only be undertaken if the samples were cohesive and fine-grained (ie porewater did not freely drain from the samples on collection).

It is preferable to determine tritium activity concentration directly in the groundwater although, in principle, the tritium activity concentration in the soil porewater and in the groundwater should be identical if the porewater and the mobile groundwater that is sampled by pump testing are in close contact. Analysis of tritium in soils may be appropriate at an early stage of a characterisation programme, in order to evaluate whether a potential problem exists. If tritium contamination below the groundwater table is detected, it is best practice to install groundwater monitoring boreholes and to obtain groundwater samples for further analysis.

Box 6.13 Gamma spectrometry

Gamma spectrometry detects gamma radiation, which is produced during the decay of most radionuclides. However, as shown in Boxes 2.2 and 2.3, there are some potential radioactive contaminants, such as ^{90}Sr, that do not produce gamma radiation on decay and whose presence cannot be inferred from short-lived gamma-emitting daughter radionuclides.

In **soil samples**, gamma spectrometry is ideal as a complementary screening measurement to gross alpha/beta. The required sample size is in the range 100 g to several kilograms. This is significantly larger than that required for gross alpha/beta analysis; hence sub-sampling errors will be smaller and results will probably be more representative of in-situ conditions. In particular, activities of common man-made radionuclides, such as ^{137}Cs and ^{60}Co, and of the natural series decay chains (headed by ^{235}U, ^{238}U and ^{232}Th) can be measured or inferred.

However, because not all radionuclides will be detected using gamma spectrometry, the technique should not be used in isolation unless the radionuclide fingerprint of the contaminated site is well understood and there is confidence that total levels of radioactive contamination can be derived from the gamma spectrometry data.

In **waters**, gamma spectrometry is typically used to provide more detailed analysis of contaminated samples. This is principally because gross alpha/beta analysis of waters provides accurate and precise measurement to detection limits below activity levels that are of radiological concern. Indeed, the detection limits of gamma spectrometry typically exceed those of the gross alpha/beta technique.

Flowsheets suggesting possible strategies for gross radioactivity and radiochemical analysis of soils and groundwaters are given in Figures 6.4 and 6.5.

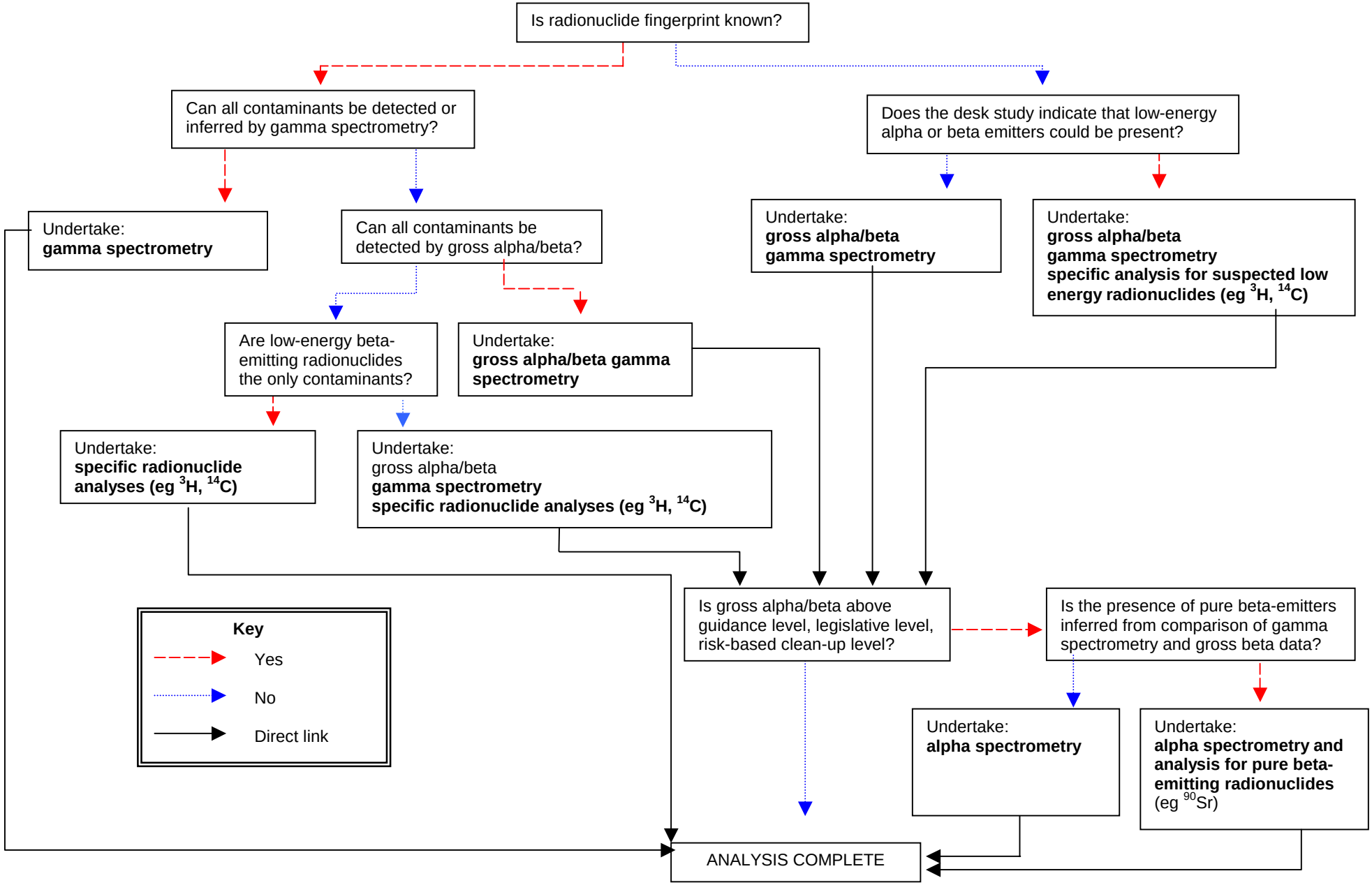

Figure 6.4 Soil analysis (for radionuclide determination)

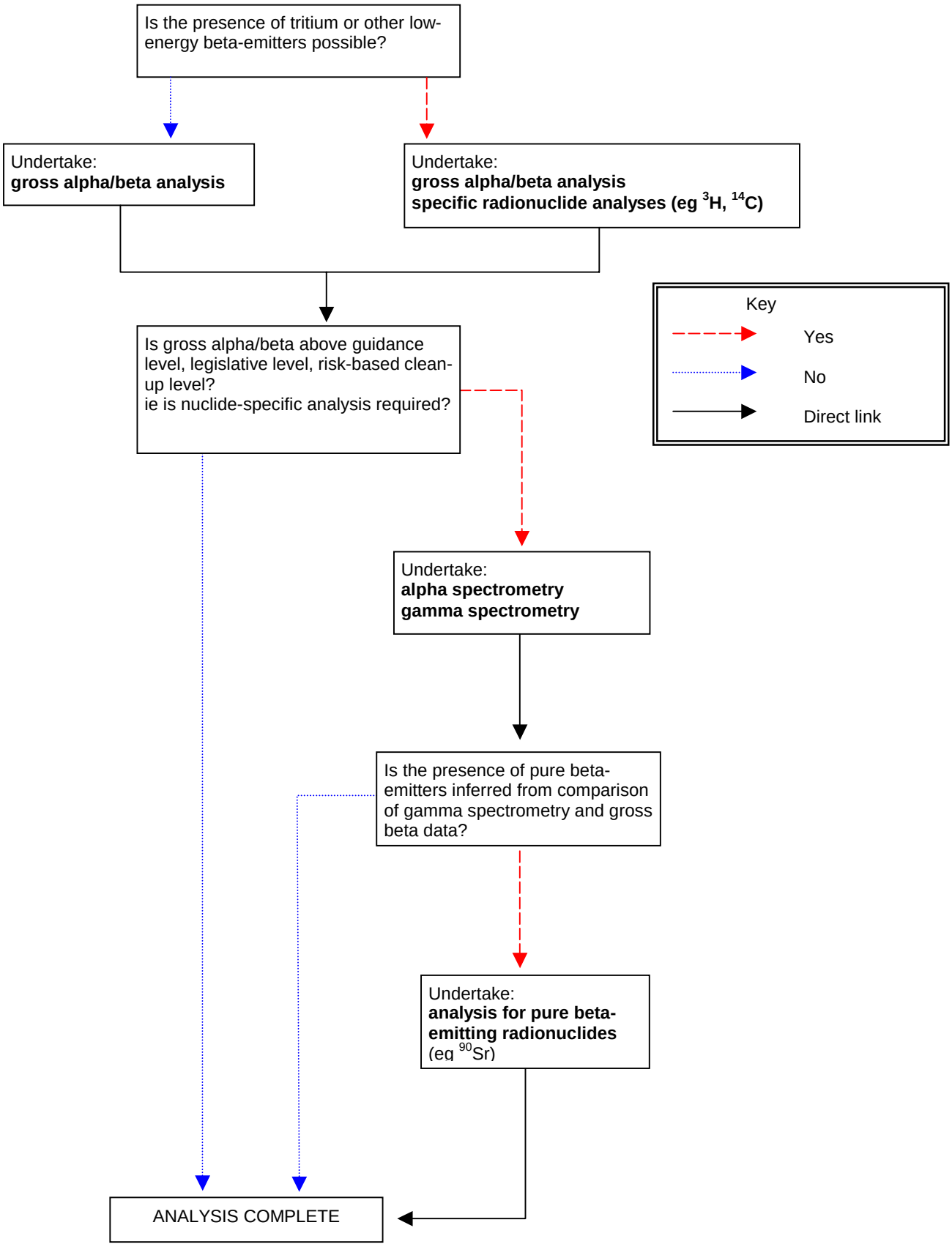

Figure 6.5 Water analysis (for radionuclide determination)

6.4.5 Assessment of errors

The confidence that can be placed in any chemical or radiochemical analytical result is influenced by two factors:

- the precision and accuracy of the analytical technique ("analytical errors")
- the extent to which the sample submitted for analysis is representative of the sample supplied to the laboratory ("sub-sampling errors").

Analytical errors are evaluated and controlled by the testing laboratory through the application of a quality control (QC) system. Details will vary, but use of the types of QC samples described in Box 6.14 should be standard practice.

Box 6.14 Quality control samples

Use of the types of QC samples described below should be standard practice.

Blanks. Materials that do not (or should not) contain the chemical or radionuclide being analysed for. Ideally, the blank should be of a similar material ("matrix") to the samples being tested. A variety of blanks may be used, to determine the potential for contamination of the samples at various stages of the sample collection and analysis procedure.

Field/method blank. (Typically applicable to water sampling). A radionuclide/chemical-free sample that is taken to the field and then processed, transported and analysed in the same manner as the actual samples.

Analytical blank. A radionuclide/chemical-free material used in the analytical testing laboratory to evaluate background contamination and cross-contamination.

Duplicate samples. Samples taken either to assess reproducibility of the field sampling procedure ("field duplicates") or to enable inter- or intra-laboratory comparison ("split samples"). Note: it is very difficult to collect duplicate soil samples as contaminant concentrations may vary over very small distances, however, duplicate samples of waters should yield the same result.

Standard samples. Samples that contain known concentrations of the chemical or radionuclide being analysed for. These samples may be used by the analytical testing laboratory as a check on analytical results or may be submitted with the batch of samples for analysis. Typically, only standard solutions would be submitted in the latter case, because of the difficulty of preparing homogeneous soil samples.

External quality control samples. Samples of material spiked with a level of radioactivity known only to an external laboratory. These are tested alongside the field samples, to provide reassurance that the analyses are correct.

6.5 REFERENCES

AEA Technology, 1998. *The Radiochemical Manual* (Produced under the National Measurement System for Ionising Radiation Metrology Programme 1995-1998, DTI). AEA Technology plc.

British Standards Institution (BSI), 1990. *Methods of Test for Soil for Civil Engineering Purposes*. BS1377: 1990. BSI. London.

British Standards Institution (BSI), 1999a. *Code of Practice for Site Investigations.*. BS5930: 1999. BSI. London.

British Standards Institution (BSI), 1999b. *Investigation of Potentially Contaminated Sites.* BS DD 175. (Revision in draft September 1999.)

CIRIA, 1992. *Methane and Associated Hazards in Construction: a Bibliography*. Special Publication 79. CIRIA. London.

CIRIA, 1993a. *Methane: Its Occurrence and Hazards in Construction*. Report 130. CIRIA. London.

CIRIA, 1993b. *The Measurement of Methane and Other Gases from the Ground*. Report 131. CIRIA. London.

CIRIA, 1995. .*Methane Investigation Strategies*. Report 150. CIRIA. London.

CIRIA, 1995. *Remedial Treatment for Contaminated Land. Volume III: Site Investigation and Assessment*. Special Publication 103. CIRIA. London.

Environment Agency, 1999a. *Technical Support Material for the Regulation of Radioactively Contaminated Land*. R&D Technical Report.

Environment Agency, 1999b. "Monitoring of Landfill Sites. Guidance on Monitoring of Landfill Leachate, Groundwater and Surface Water. Main Guidance Document". Draft for consultation, August 1999.

Environment Agency, 1999c. *Decommissioning Redundant Boreholes and Wells*. National Groundwater and Contaminated Land Centre.

Environment Agency, 2000. *Review of Non-invasive Investigation Techniques for Groundwater Pollution Studies*. R&D Report P2-178 (draft).

Fetter, C W, 1992. *Contaminant Hydrogeology*, Macmillan Publishing Company.

Health and Safety Executive, 1988. *Avoiding Danger from Underground Services*. HS(G)47. HSE Books. Sudbury.

Scottish Enterprise, 1994. *How to Investigate Contaminated Land: Requirements for Contaminated Land Site Investigations.* Scottish Enterprise.

United States Environmental Protection Agency (USEPA), 1997. *Multi-agency Radiation Survey and Site Investigation Manual (MARSSIM).* Report EPA 402-R-97-016.