Technical Support Materials for the Regulation of Radioactively Contaminated Land

R&D Technical Report P307

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Research Contractor:
Entec UK Ltd

And

National Radiological Protection Board

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EXECUTIVE SUMMARY

Introduction

This report has been prepared by Entec UK Ltd in conjunction with the NRPB on behalf of the Environment Agency and the Department of the Environment, Transport and the Regions. The purpose of the report is to provide technical information to support consideration of a new regulatory regime for the control of radioactively contaminated land.

Radioactive Land Contamination in the UK

The occurrence of radioactively contaminated land and UK experience in its remediation has been reviewed. Radioactive contamination in the UK has primarily arisen from historical industrial practices such as luminising using radium, gas mantle manufacture, phosphate manufacture and use, metal ore refining and processing and various other industrial and medical uses of radioisotopes. The UK situation is dissimilar to other major international occurrences of contamination, as large scale contamination problems associated with uranium extraction, under regulated nuclear activities and weapons testing do not exist. Radioactive contamination in the majority of cases is of natural origin which has been enhanced for a particular product use (e.g. radium luminising paint) or inadvertently created as a by product (e.g. tin slag). Radium, uranium, thorium, strontium, promethium and their decay products are most commonly recorded. Contamination has most usually occurred as a result of historically uncontrolled waste disposal practices.

Identifying Potentially Contaminated Sites

A simple desk based approach has been proposed to assist regulatory bodies in identifying potentially radioactively contaminated sites of concern in their geographical area. This is based on a two tier approach. Firstly a simple qualitative approach to ranking potentially contaminated sites in order to rapidly and cost effectively focus on sites of prime concern. This is based on the potential occurrence of radioisotopes identified for the various land uses and takes into account the probability of occurrence of radioactive contamination and the possible severity of the radiological hazard. Secondly a site specific desk study drawing on established methodologies from the DETR contaminated land research programme.

Characterisation Techniques

A review of field and laboratory methods for the assessment of radioactive contamination has been undertaken. The review has considered both direct monitoring techniques, for example when assessing gamma emitters and conventional sampling and analysis methods for other circumstances. A broad range of detector based technologies have been investigated for direct monitoring ranging from simple hand-held, off-the-shelf, health physics instrumentation to aerial surveys. The advantages and limitation of each technique are discussed and the techniques most appropriate for the principal radioisotopes of concern are identified. Sampling and analysis protocols are described with consideration of appropriate sampling density, distribution of sampling points and analytical techniques being considered.

Assessing and Categorising the Significance of Radionuclides on Land

A practical methodology is proposed to enable the assessment of unacceptable risks to health from radioactively contaminated land and assist the determination of appropriate remediation.

Contaminated land problems may arise either as a result of land redevelopment (change of use) or during ongoing use of the land these have been considered under the ICRP system of protection as 'practice' or 'intervention' situations. In general terms land redevelopment is considered to be a 'practice' whereas land that is already in use when the contamination is identified is an 'intervention'.

The NRPB method for assessment of radiological risks from contaminated land has been compared to the method used to develop UK guideline values for chemically contaminated land (CLEA). The two approaches are in many respects very similar but some significant differences in scenarios considered and parameters used were identified that may require further assessment if comparability is to be achieved.

Dose criteria are proposed for intervention situations where no change of use is envisaged. If radioactively contaminated land gives rise to an individual dose of in excess of 10 mSv/year remedial measures are always justifiable, for doses below 0.3 mSv/year remedial measures are rarely justifiable. For doses in between these values intervention will require justification on a site specific basis. For each of the radioisotopes of concern, risk based 'screening' levels in Bq/g have been established that would result in the above dose levels for two situations: uniform surface contamination, and buried or heterogeneous contamination.

A two tier methodology for assessing land is proposed. Firstly, an initial 'screening assessment' which would involve a desk study and initial site survey followed by categorisation against the 'screening' levels. Secondly, a site specific assessment for sites not cleared on screening including a detailed radiological assessment of current dose levels and projected dose levels and an assessment of the benefits/disbenefits of remediation (intervention).

Remediation Technologies and Experience in the UK

Within the United Kingdom, there is limited experience in the remediation of radioactively contaminated sites. Most of this experience has been obtained on MOD sites where contamination has resulted from *ad hoc* disposal of radium luminised items; luminising works; rare-earth ore processing operations; and contamination arising from uncontrolled disposal of radioactively contaminated wastes. Experience is most common for sites contaminated with radium-226, thorium-232, caesium-137 and uranium. Remediation schemes have generally involved the use of simple, robust methodologies such as excavation and off-site disposal, using standard health physics instrumentation for the identification and segregation of contamination.

The applicability to radioactively contaminated sites of using other remediation technologies commonly employed on chemically contaminated land is reviewed. These are categorised according to standard civil engineering technologies including excavation, covering systems and barriers, and process based technologies including physical treatment, biological, chemical, thermal and solidification treatment methods. Of the more innovative techniques, only soil washing and phytoremediation have seen limited application at pilot scale in the UK. There has been more widespread application outside the UK of soil washing and vitrification techniques; however, these have not been considered in detail in this report.

Regulatory Issues

The principal current legislation and regulatory instruments of relevance to the assessment and remediation of radioactively contaminated land have been reviewed and potential conflicts with respect to the proposed regulatory regime have been considered.

One potential conflict is that, under the proposed risk based regime, situations may arise where sites will be classified as not being radioactively contaminated when, under the definition of RSA93, radioactive materials may still be present. The implications of this on public and site user confidence need to be considered.

An important concern in the UK is the availability of disposal routes for low level wastes because the BNFL Drigg facility has a limited capacity. Therefore, it may be necessary to consider the greater use of landfills for wastes which represent a low radiological hazard. The implications of this for site licensing and for the safe handling of wastes at landfill sites that may not be designated as radioactive waste but nevertheless contain discrete radioactive sources needs to be considered. In this regard clearer regulatory guidance is needed on what is an acceptable averaging volume for consigning wastes to landfill.

Recommendation

Prior to its wider application throughout the UK, it is recommended that the methodology proposed for identifying contaminated sites is piloted in a region/area where a range of contamination situations might be expected. It would be beneficial, following initial site identification, to undertake a select number of site specific desk studies and screening surveys to better understand the nature of contaminant distribution that might occur on such sites, in order that the extent and likely occurrence of intervention situations arising from the implementation of the proposed regime can be assessed.

Since the risk assessment model used has some differences in parameters compared to the model used for the chemically contaminated land regime, and since it is desirable that there is as much consistency as possible between the radioactive and chemically contaminated regimes, it is recommended that further work is undertaken to examine the impact upon screening levels of using, wherever possible, consistent parameters. It is recommended that the finalised risk model should be tested on some existing well-characterised sites to assess its performance in identifying the need for intervention.

The information in this report combined with other source material and recommended supplementary work should provide a basis for developing training materials for the relevant authorities and responsible staff.

KEYWORDS

Activity concentration	The activity per unit mass of a material, measured as the number of Becquerels per gramme, or Bqg^{-1}.
Change of use	A situation where a site is redeveloped to a different land use than that previously. Planning permission is required for changes of use out with certain land use classes, elaborated further in Section 6.
Characterisation	The process by which the nature, extent, location and severity of contamination on a site is assessed.
Intervention	An operation where the overall radiation exposure is reduced by influencing the existing situation; by removing existing sources, modifying pathways, or reducing the number of exposed individuals. Intervention should be justified and optimised.
Radioactive Material	At the present time, several definitions exist for "radioactive material", within the Radioactive Substances Act 1993, the Ionising Radiations Regulations 1985 and the Radioactive Materials (Road Transport) Regulations, 1996.
Remediation	Any action performed to deal with an environmental problem.
Validation	The process which occurs as a final stage in a remediation project, and which allows the detection of any remnant activities and volumes remaining after the remediation exercise has been carried out. Validation must be scoped to provide confidence to all stakeholders in the quality of the remediation.

1. INTRODUCTION

1.1 Terms of Reference

Entec, supported by the National Radiological Protection Board (NRPB), was commissioned by the Environment Agency and the Department of the Environment, Transport and the Regions (DETR) to provide technical support in considering a new regulatory regime for the control of radioactively contaminated land. This work was to summarise previous practices in the identification of radioactively contaminated land and consider the implications of implementing the new regulations.

The aims and objectives are set out in the Environment Agency Specification (the Specification) for the project attached in Appendix A and briefly comprise:

i) The provision of authoritative information on identification techniques for potentially contaminated sites, their characterisation, assessment of resulting doses and risks, and their remediation.

ii) The provision of criteria for use in the UK during the characterisation and remediation of radioactively contaminated land, commensurate with those used for other forms of contaminated land in the UK.

iii) The provision of recommendations for guidance material to be issued by statutory bodies, and content of guidance material issued to and training used by regulators.

Specific details on report structure are also set out in the Specification. The study is set out within several tasks, each of which address some aspect of the radioactively contaminated land issue.

These tasks comprise:

Number	Task Outline
One	A review of radioactively contaminated land in the UK
Two	A case study review of radioactively contaminated sites which have been remediated
Three	Criteria for the designation of radioactively contaminated land. This Task is reported as a separate report (Report No DETR/RAS/99.010 Entec reference 00769RR112)
Four	Techniques applicable for the identification of radioactively contaminated sites
Five	A review of site characterisation techniques
Six	Evaluation of dose and risk assessment methodologies
Seven	A review of remediation techniques applicable to radioactively contaminated land
Eight	Regulatory responsibilities
Nine	Areas requiring resolution

1.2 Origin and Audience of Study

The study was commissioned to meet the anticipated requirements of:

- Department of the Environment, Transport and the Regions (DETR), Welsh Office, Scottish Office
- Environment Agency (England and Wales), Scottish Environment Protection Agency (SEPA), Environment and Heritage Service, Department of the Environment (Northern Ireland).

1.3 Legislative and Regulatory Framework

1.3.1 Background

A regulatory regime specifically aimed at radioactively contaminated land has been proposed (DETR, 1998). This is intended to specify remediation of historically contaminated sites posing unacceptable risks. This would mirror the chemically contaminated land regime, from which radioactive contamination is specifically excluded.

Under Part IIA of the Environmental Protection Act (EPA) 1990, inserted by Section 57 of the 1995 Environment Act, provision has been made for the production of regulations to address radioactively contaminated land. To develop the principles of a control regime for radioactively contaminated land, a consultation paper "Control and Remediation of Radioactively Contaminated Land" was published by the Department of the Environment, Transport and the Regions on 26 February 1998, seeking views from interested parties. This study is a further step in the process of developing a regulatory regime and aims to satisfy the responsibilities of the statutory bodies to compile guidance to the Agencies to achieve their policy objectives, and the Agencies' need to compile and disseminate appropriate information on techniques.

1.3.2 Contaminated Land Provisions of the Environmental Protection Act (Part IIA)

The proposed regime for the control of radioactively contaminated land is to follow the framework established in Part IIA EPA 1990 for chemically contaminated land, effective from early 2000. This sets out the nature of liabilities that can be incurred by owners of contaminated land and groundwater, and allows for the identification of chemically contaminated land which poses a threat of significant harm to human health or the environment, or the pollution of controlled waters. Central to the new regulatory system is a rigorous procedure of risk assessment which is used to determine the existence of "contaminated land", according to the new definition. The approach also embodies the established principles of "sustainable development" and the "polluter pays", with a "suitable for use" approach to remediation requirements.

Contaminated Land Definition

According to the Act, "contaminated land" is defined as that which is in such a condition that:

- **significant harm** is being caused or there is a **significant possibility** of such harm being caused; or
- **pollution of controlled waters** is being, or is **likely to be**, caused.

The definition of what harm is to be regarded as significant will be set out in statutory guidance and will include defined effects to human beings, ecological systems and property.

Under the risk assessment procedure, for such harm to the non-aquatic environment or pollution of controlled waters to be possible, there must be a "pollution linkage", as follows:

- a **source** (contaminant);
- a **pathway** by which a receptor is or would be exposed or affected;
- a **receptor** which is or would be affected by the contaminant. This includes human beings, other living organisms, controlled waters (including groundwater beneath the site) and property.

If any part of this linkage is absent, no harm is possible, and so the land is not "contaminated". In the context of contaminated land, "risk" can be defined as a combination of two factors:

- the probability, or frequency, of occurrence of a defined hazard (for example, exposure to a property of a substance with the potential to cause harm); and
- the magnitude (including the seriousness) of the consequences to a specified receptor.

Remediation and Intervention

Part IIA also provides for the enforcing authority to ensure that appropriate and cost-effective remediation is carried out to deal with the problem, either voluntarily, or by way of a remediation notice. It therefore provides a mechanism to deal with those sites which are causing concern now because of the presence of chemical contamination, and which would not otherwise be dealt with through other pollution control legislation, or under the planning system.

The liability for the costs of remediation falls on the "appropriate person" who is defined by the application of the "polluter pays" principle, as one "who caused or knowingly permitted the contaminating substance to be on, in or under the land", i.e. a Class A person.

If such a person cannot be identified, the liability transfers to a Class B person, i.e. the owner or occupier. There is a complex system of exclusions and apportionment which takes into account the possibility of the existence of several persons being held responsible to differing degrees.

Owing to the potential legacy of radioactively contaminated sites, the proposed regime for radioactively contaminated land will operate within the conceptual framework established by the International Commission on Radiological Protection (ICRP), in their Publication 60. This lends a further aspect to the proposed regime, in that regulatory action will only take place on the established ICRP "Intervention" basis, where unacceptable risks associated with the current use of land arise. Further explanation of ICRP definitions is given below.

Remediation of chemically and radioactively contaminated land has historically been performed in the case of a "change of use" to make the land fit for the future use. However, the new chemically contaminated land legislation makes the provision for land that is identified to be causing, or pose a risk of causing "harm" or pollution of controlled waters, to be remediated, irrespective of changes of use. Such an approach is proposed for radioactively contaminated land, and fits into the ICRP "Intervention" framework.

1.3.3 Existing Regulatory Framework for Radioactive Substances

The legislative history associated with radioactivity is of fairly recent origin. There were Luminising Regulations issued in 1947, although these only applied to substances used for the production of luminescent material, chiefly radium. Other than for Luminising Works, very little regulation took place before 1960, when most installations routinely using unsealed sources of radioactivity were under Government control, until the introduction of the Radioactive Substances Act (RSA) 1960. This has been updated into the Radioactive Substances Act 1993, however many of the Exemption Orders operating under the previous legislation still remain active although they are currently under review. Health and safety aspects of working with radioactivity were first addressed in the Ionising Radiations (Unsealed Radioactive Sources) Regulations 1968, which were revoked by the 1985 Ionising Radiation Regulations.

Consequently, three main pieces of legislation currently exist in the UK of interest to the study:

- **Radioactive Substances Act, 1993**; this legislation deals with protection of the public and the environment from the discharge or disposal of radioactive substances, and requires authorisation for accumulation and disposal of radioactive wastes and registration of the keeping, and use of radioactive materials;
- **Ionising Radiations Regulations, 1985**; concerned with the protection of workers and members of the public from hazards arising from the use of radioactive materials and other sources of ionising radiation in the workplace;
- **The Radioactive Material (Road Transport) Regulations (RMRT), 1996**; controlling the transport of various materials by road, with several exceptions and exemptions.

Definition of Radioactive Material

At the present time, a number of different definitions exist for "radioactive material". Those chiefly of interest lie in the UK legislation; the Ionising Radiation Regulations, 1985, and the Radioactive Substances Act, 1993. Section One of this latter source defines radioactive material as being material that:

"... is a substance to which this subsection applies or an article made wholly or partly from, or incorporating, such a substance".

The Act then describes "substances" as either containing natural radioelements specified in an attached Schedule (Schedule One, Table 1.1) or having been artificially subjected to nuclear fission or bombardment with neutrons or ionising radiation. If natural radioelements are present below the specified activity concentration, the substance is not radioactive material within the meaning of the Act.

Table 1.1 Schedule One Elements from RSA, 1993

Element	Activity – Becquerels per gramme (Bq/g)		
	Solid	Liquid	Gas/Vapour
Actinium	0.37	$7.4*10^{-2}$	$2.59*10^{-6}$
Lead	0.74	$3.7*10^{-3}$	$1.11*10^{-4}$
Polonium	0.37	$2.59*10^{-2}$	$2.22*10^{-4}$
Protoactinium	0.37	$3.33*10^{-2}$	$1.11*10^{-6}$
Radium	0.37	$3.7*10^{-2}$	$3.7*10^{-5}$
Radon	-	-	$3.7*10^{-2}$
Thorium	2.59	$3.7*10^{-2}$	$2.22*10^{-5}$
Uranium	11.1	0.74	$7.4*10^{-5}$

(RSA (1993) Schedule One Specified Elements.)

The Ionising Radiation Regulations (currently under revision), aimed at protecting peoples' health and safety while working with radioactive materials, define a "radioactive substance" as one which:

"*... having an activity concentration of more than 100 Bq/g and any other substance which contains one or more radioisotopes whose activity cannot be disregarded for the purposes of radiation protection, and the term includes a radioactive substance in the form of a sealed source.*"

Further definition is given in the RMRT Regulations, 1996, which includes a table of elements and their radioisotopes, and activities for special and non-special (i.e. dispersible) forms of each radioisotope as Schedule 36. The maximum permissible activity for transport constraints is then given by a factor multiplier of the maximum activity of the special or non-special form material, specific to several specifications of transport container.

Exemption Orders

Under RSA 1993, a number of Exemption Orders exist which provide exemption, usually subject to conditions, from the need for registration, and/or authorisation. Current Exemption Orders are listed in Table 1.2. Many Exemption Orders have been constructed to relate to specific practices, and recognise the varying degrees of risk attached to different radioisotopes, as well as the implications of their disposal routes. These Orders allow the disposal of materials that may be "radioactive" under the Act to suitably licensed local waste disposal facilities by "exempting" them below defined activity levels, while beyond this the material may be defined as e.g., Low Level waste. This material may be stored at the producing, licensed, establishment, or sent to Harwell for storage or Drigg licensed radioactive waste disposal facilities.

Table 1.2 Current Conditional Exemption Orders

Title	Statutory Instrument Number
Natural Radioactivity	
Phosphatic Substances, Rare Earths etc.	1962/2648
Lead	1962/2649
Uranium and Thorium	1962/2710
Prepared Uranium and Thorium Compounds	1962/2711
Geological Specimens	1962/2712
Precipitated Phosphate	1963/1836
Products containing Radioactivity	
Electronic Valves	1967/1797
Gaseous Tritium Light Devices	1985/1047
Testing Instruments	1985/1049
Smoke Detectors (as amended)	1980/953 & 1991/477
Luminous Articles	1985/1048
Specific types of Undertaking	
Exhibitions	1962/2645
Storage in Transit	1962/2646
Schools etc	1963/1832
Hospitals (as amended)	1990/2512 & 1995/2395
Waste Disposal	
Waste Closed Sources	1963/1831
Other	
Substances of Low Activity	1986/1002

After DETR (1999).

Different Exemption Orders vary in the way they express radioactive substances. For example, the Phosphatic Substances Exemption Order, like the Act itself, refers to the radioactivity of different elements, as opposed to radioisotopes. Thus all isotopes of the relevant elements that may be present must be taken into account. In contrast, the RMRT Regulations refer to separate radioisotopes.

Although not aimed at contaminated land *per se*, the RSA is still applied to contaminated land situations. It is interpreted that the contaminated medium becomes waste as soon as it is excavated, and so the RSA applies, controlling the disposal of the material.

"Practices" and "Interventions"

The present system of radiological protection recommended by the International Committee on Radiological Protection in its Publication 60 (ICRP, 1990), divides the variety of radiological licensing and regulation issues into two types: practices and interventions. Different sets of criteria exist for each type of situation, which will vary to account for local necessity. The system of protection is designed to prevent the occurrence of harmful effects by keeping doses below relevant thresholds.

i) **Practices**: refers to adding radiation exposures through the addition or modification of new sources, pathways and individuals. A practice should be assessed so as to present the maximum benefit to the individual or society, although the inequity caused by the differing needs of the two targets must be minimised. Three principles comprise the system for practices:

- *Justification.* No practice involving exposures to radiation should be adopted unless it produces sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes;
- *Optimisation.* In relation to any particular source within a practice, the magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures where these are not certain to be received should all be kept As Low As Reasonable Achievable (ALARA), economic and social factors being taken into account. This procedure should be constrained by restrictions on the doses to individuals (dose constraints), or the risks to individuals in the case of potential exposures (risk constraints), so as to limit the inequity likely to result from the inherent economic and social judgements;
- *Individual Dose and Risk Limits.* The exposure of individuals resulting from the combination of all the relevant practices should be subject to dose limits, or to some control of risk in the case of potential exposures. These are aimed at ensuring that no individual is exposed to radiation risks that are judged to be unacceptable from these practices in any normal circumstances.

ii) **Interventions**: refers to decreasing the overall radiation exposure by influencing the existing situation; by removing existing sources, modifying pathways, or reducing the number of exposed individuals. Dose limits do not apply in the case of Intervention, although the two principles below can lead to intervention levels which will give guidance whether intervention is justified. There will be a level at which intervention is always justified, due to deterministic effects.

- *Justification.* The proposed intervention should do more good than harm, i.e. the reduction of detriment resulting from the reduction in dose should be sufficient to justify the harm and the costs, including social costs, of the intervention;
- *Optimisation.* The form, scale and duration of the intervention should be optimised so that the net benefit of the reduction of dose, i.e. the benefit of the reduction in radiation detriment, less the detriment associated with the intervention, should be maximised.

Further elaboration on these aspects is given in ICRP (1990) and Mobbs *et al* (1998).

Land contaminated with radioisotopes can fall between the two definitions of a practice or intervention. Mobbs *et al* (1998) detail radioactively contaminated land problems to fall into one of two categories:

i) A change of use is proposed that is intended or expected to increase public use of an area of land that is known to be contaminated, e.g. redevelopment of an industrial site for housing. In this case, assuming that not all of the contamination is removed, new groups of people will become exposed to an existing (and currently controlled) source, indicating that the system of control for practices should be used. The practice itself may no longer exist, but the exposures would continue to be regarded as a subset of the original practice;

ii) Contamination is discovered on land to which the public already have access but for which there is no planned change of use, e.g. land that has already been developed as a housing estate. In this case, exposures will already be occurring – the source, exposure pathways and exposed people are already in place – and therefore this situation should be considered as a candidate for intervention.

It should be noted that dose limits do not apply to intervention situations, as the exposure is already occurring, and as such any positive action will decrease it. With the practice situation, there is an element of choice in the decision whether to permit the practice, and increase exposure, or to prevent it and not cause an increase in exposure. For example, a site known to be contaminated and proposed for redevelopment from an industrial to housing end use, may or may not be allowed to be developed depending on the amount of active material still present, the feasibility and method of remediating it, and the final remediation criteria permitted.

Work activities undertaken when remediating a site will come under IRR85, as with any work undertaken with radioactive materials (HSE, 1999).

The latest Euratom Basic Safety Standards Directive, Euratom 96/29 has resulted in proposed revisions to the arrangements made under RSA 1993 for which DETR (1999) has sought consultation responses. The Directive is organised around a number of Titles detailing the scope of the Directive, requirements for reporting and authorisation of practices, justification, optimisation and dose limitation, operational health and safety aspects, natural radiation and the intervention case. The latter Title is of most pertinence to the study, and applies to cases of radiological emergencies or in cases of lasting exposure resulting from the after-effects of a radiological emergency or a past or old practice or work activity. The Directive states that, in line with the ICRP 60 approach, dose limits shall not apply to Intervention. However, it also notes that Intervention levels established in the application of an Article dealing with radiological emergencies of various types may "... constitute indications as to the situations in which intervention is appropriate". Section II of Title IX, "Intervention in Cases of Lasting Exposure", Article 53, requires that Member States ensure that:

- The area concerned is demarcated and access to/use of facilities within this area is regulated;
- Exposure monitoring arrangements are made;
- Any appropriate intervention is implemented with respect to site specific conditions.

1.4 Definitions and Elementary Radiochemistry

1.4.1 Types of Radiation

The accepted structure of the basic unit of material, the atom, is well documented to consist of neutrons, protons and electrons. Protons, the subatomic unit of positive charge, determine the physical properties of the atom which they make up; for example, all atoms with one proton in the nucleus, regardless of the quantity of neutrons and electrons, behave as hydrogen.

There are certain atoms that are not physically stable, and require internal rearrangement to regain a balanced arrangement of neutrons, protons and electrons. The matter or energy ejected during these internal rearrangements, or radioactive decay, is known as radiation, of which there are several types; alpha, beta, gamma, X-rays and neutrons.

i) **Alpha**: alpha radiation comprises helium nuclei (two protons and two neutrons), ejected from the nucleus of the radioactive atom undergoing decay. Owing to the size and mass of the particle, alpha radiation can be controlled with relatively thin materials, although it dissipates energy over a short path length. This latter property makes an alpha emitting isotope particularly significant when dealing with an internal radiation dose. They can cause considerable cell damage if ingested.

ii) **Beta**: when a neutron splits to produce a proton, the missing constituent of its mass is ejected as an electron. These are known as a beta particles, and are more penetrative than alpha particles. They can penetrate the outer layers of skin but are stopped by perspex, glass or aluminium.

iii) **Gamma**: following emission of alpha and/or beta particles, a further rearrangement in the radioactive nucleus can occur. This can involve the release of nuclear packing energy, or gamma radiation, which is electromagnetic in nature and behaves as photons. Gamma radiation is far more penetrating than alpha or beta particles and can pass through most materials but will usually be stopped by steel, lead or concrete.

iv) **X-Rays**: X-Rays are produced when an electron is stopped in material, and can also be produced when an incoming electron has sufficient energy to displace an inner orbit electron. Outer orbit electrons are attracted, and X-Rays are the emission of the difference in orbital energies.

v) **Neutrons**: are the most penetrating particles and require a substantial thickness of concrete or water to prevent health risks.

1.4.2 Activity and Dose Measurements

The basic unit of radioactive measurement is the Becquerel, representing one radioactive decay per second. From half-life calculations, the actual physical mass of the radioactive element can be calculated from this quantity. However, in terms of radioactively contaminated land, the units of interest represent the activity per unit mass of material, or Becquerel/gramme (Bqg^{-1}), which allow an isotope specific calculation of radiological energy and consequent risk to be made.

Ionisation will alter atoms and molecules, and thus will sometimes change biological cells of which these structures form a part. Damage to the cells, improperly repaired, will result in the cell either not being capable of surviving or reproducing, or will result in a surviving modified cell. Observable harm will result to tissues and organs of the body with increasing levels of ionisation, with the probability and severity of harm increasing statistically with the dose. This type of effect is termed “deterministic”. The other effect, termed “stochastic”, results from the reproduction of a modified viable cell, which may result in the manifestation of a malignant condition, or cancer, the severity of which is not altered by the intensity of the original dose. This may also manifest itself in a hereditary way, where the damaged cells transmit genetic information to their progeny.

Basic units of biological dosimetry include the following, also summarised in Table 1.3:

i) **Absorbed Dose**: absorbed dose is defined as the energy absorbed per unit mass, measured in grays (Gy – units of joules per kilogram).

ii) **Equivalent Dose**: this is given by the absorbed dose averaged over the tissue or organ, weighted with an appropriate radiation weighting factor with units of sieverts (Sv), also in joules per kilogram. This is to account for the varying types and energies of the incident radiation, which have been found to affect the probability of stochastic effects.

iii) **Effective Dose**: this is also measured in joules per kilogram, and is given the unit sieverts. The effective dose provides further weighting to account for the varying susceptibility of tissues to damage.

iv) **Others**: further dose definitions are made for doses emanating from a source that has been ingested into the body, and the collective dose to an exposed group.

Table 1.3 Ionising Radiation Quantities and Units

Quantity	SI Unit	In other SI units	Old unit	Conversion Factor
Exposure	-	C kg-1	Röntgen (R)	1 C kg-1 ~ 3876 R
Absorbed Dose	gray (Gy)	J kg-1	Rad (rad)	1 Gy = 100 rad
Dose Equivalent	sievert (Sv)	J kg-1	Rem (rem)	1 Sv = 100 rem
Activity	becquerel (Bq)	s-1	Curie (Ci)	1 Bq ~ 2.7E-11 Ci

Radiation is both a naturally and artificially occurring phenomenon, and some idea of the relative contributions may be gained from the pie chart below, sourced from NRPB (1994). It can be seen that the *average* radiation dose in the UK is made up of a number of constituent contributing parts, the most significant of which is radon gas. Truly artificial radiation constitutes a very small contribution to the overall dose.

Radioisotopes

There is a wide range of radioactive material, arising through either natural activity, enhanced natural activity, or activity induced through irradiation. Some common radioisotopes and decay chains are outlined in Appendix B, which includes the uranium, thorium and actinide series. This study is focussed on radioisotopes which may have a risk implication in terms of land contamination. As such, there is a natural cut off point in terms of the specific radioisotope half-life, as those with short half-lives will not present a long-term hazard *per se*, although their progeny, if longer-lived, may. Consequently, a half-life criterion of five years was selected to screen out all radioisotopes of shorter half lives than this. However, it is recognised that a number of industrially important radioisotopes have half-lives of less than five years, for example promethium-147, used in "beta light" sources, and so these are included in Appendix B for completeness.

1.4.3 Discussion of Background Levels

With the ubiquitous nature of ionising radiations, it is often difficult to discriminate between what represents "natural" or "background" radiation, and what is a result of additional contaminative activity, arising from deposition of radioisotopes of anthropogenic source. NRPB (1994) quantifies the *average* background radiation dose of 2.6 mSv y^{-1} to be made up of several constituent parts, although this is an average dose. Figure 1.1 shows the constitute parts of the average UK yearly dose. Hughes and Shaw (1996), also under the auspices of the NRPB, break the average radiation dose into the following sections:

- cosmic radiation;
- natural gamma radiation from rock, soils and building materials;
- internal exposures;
- radon.

This source also presents typical ranges of activity concentrations naturally occurring in UK geology, summarised in Table 1.4.

In addition, it should be noted that background radiation doses will include doses from past practices, including atmospheric weapons tests in the 1950s and 1960s, and the Chernobyl incident. Generally, the average radiation dose due to natural radiation is made up of these contributions, which may vary according to geographical location and habitual factors. Background levels of radiation at a certain site will vary with the predominance of the above factors, although the principal variant will be the underlying geology and any differentiated units near the surface of this geology. Thus, soils underlying a site will generally reflect the nature of the underlying geology, with soils differentiated from acidic rocks reflecting their higher radioisotope concentrations. In addition, a site may have been made up with materials sourced from different geographical areas, which may distort the background radiation distribution. For example, construction materials, either in the form of imported fill to make up the site, as discussed above, or in the form of formed structural components, may have been produced from materials of elevated activity.

It is therefore possible to investigate a site and discover that the apparent background level of radiation varies across the site, with the nature of the underlying soils, infilled naturally-sourced construction materials and structural components. Drury (1995) documents the remediation of a site in East London, contaminated with radium and thorium, discussing in particular the establishment of a background control level against which the final clearance of the site could be compared. The final survey included the following steps taken to establish a reference background level:

i) A standard background measurement was made in an area sufficiently close to the site to be regarded as essentially identical in its natural background characteristics to those on the site but sufficiently remote from the site that the contamination level there resulting from the handling of radioactive material on the site would be a negligible fraction of that produced on the site;

ii) A reference background measurement was made at a readily accessible part of the site which (a) would not be disturbed during the final radiological survey operation and (b) no active material would be introduced to within 10 metres of this reference background location.

In terms of assessing the impact of a certain background level, Barraclough and McDonnell (1993) suggest a pragmatic approach which derives the appropriate artificial addition to background, and then adds this figure to the average natural concentration of the nuclide in question. This total value may then be used as a universal criterion irrespective of background, which can then be used in ALARA ("as low as reasonably achievable") assessments, as any regional or local variation of background radiation is accounted for in a corresponding reduction in the artificial component.

There is a potential issue in terms of past releases of radioactivity, where such discharges have been subject to legislative control acceptable at the time, but have now resulted in levels substantially above normal acceptable background levels. Warwick (1999) highlights the case of plutonium-241 in sediments of the Ravenglass estuary, Cumbria, the highest value of which was 114 kBq kg^{-1}. The Environment Agency "Radioactivity in the Environment" Monitoring Report for 1996 (EA, 1999) also includes details of sampling in the Ravenglass estuary, and puts the dose rate at between 0.10 and 0.12 μGy h^{-1}. The report identifies background levels for external radiation dose rates of 0.07 μGy h^{-1} and 0.05 μGy h^{-1}, for sandy and muddy substrates respectively.

Table 1.4 Activity Per Unit Mass of Natural Radioisotopes in Rocks, and Occasions of Elevated Activity Concentration

	Typical activity concentration or range (Bq kg^{-1})				
Type of rock/soil	**^{40}K**	**^{232}Th**	**^{235}U***	**^{238}U+**	**^{226}Ra+**
Igneous					
Acidic (e.g. granite)	1000	80	3	60	60
Granite	$6*10^2$-$1.8*10^3$	20-$3.5*10^2$	-	20-$5*10^2$	20-$5*10^2$
Intermediate (e.g. diorite)	700	30	1	20	20
Mafic (e.g.basalt)	240	10	0.5	10	10
Ultrabasic (e.g. durite)	150	20	0.02	0.4	0.4
Sedimentary					
Limestone	90	7	1	30	30
Carbonate	-	8	1	30	30
Sandstone	370	10	1	20	20
Shale	700	40	2	40	40
Soil	370	25	1	25	25

(Hughes and Shaw, 1996)

*Calculated using a ^{238}U/^{235}U activity ratio of 22.

+Assumed to be in equilibrium with each other, unless more information is available.

Hughes and Shaw (1996) also discuss the activities of various materials, from cement to granite bricks, (Table 1.5).

Table 1.5 Activity Per Unit Mass of Some Natural Radioisotopes in Building Materials

	Activity concentration (Bq kg^{-1})		
Material	**^{40}K**	**^{226}Ra**	**^{232}Th**
Cement	160	22	18
Concrete blocks (inc. fly ash)	430	66	37
Clay bricks	620	52	44
Granite bricks	1000	89	81

(Hughes and Shaw, 1996)

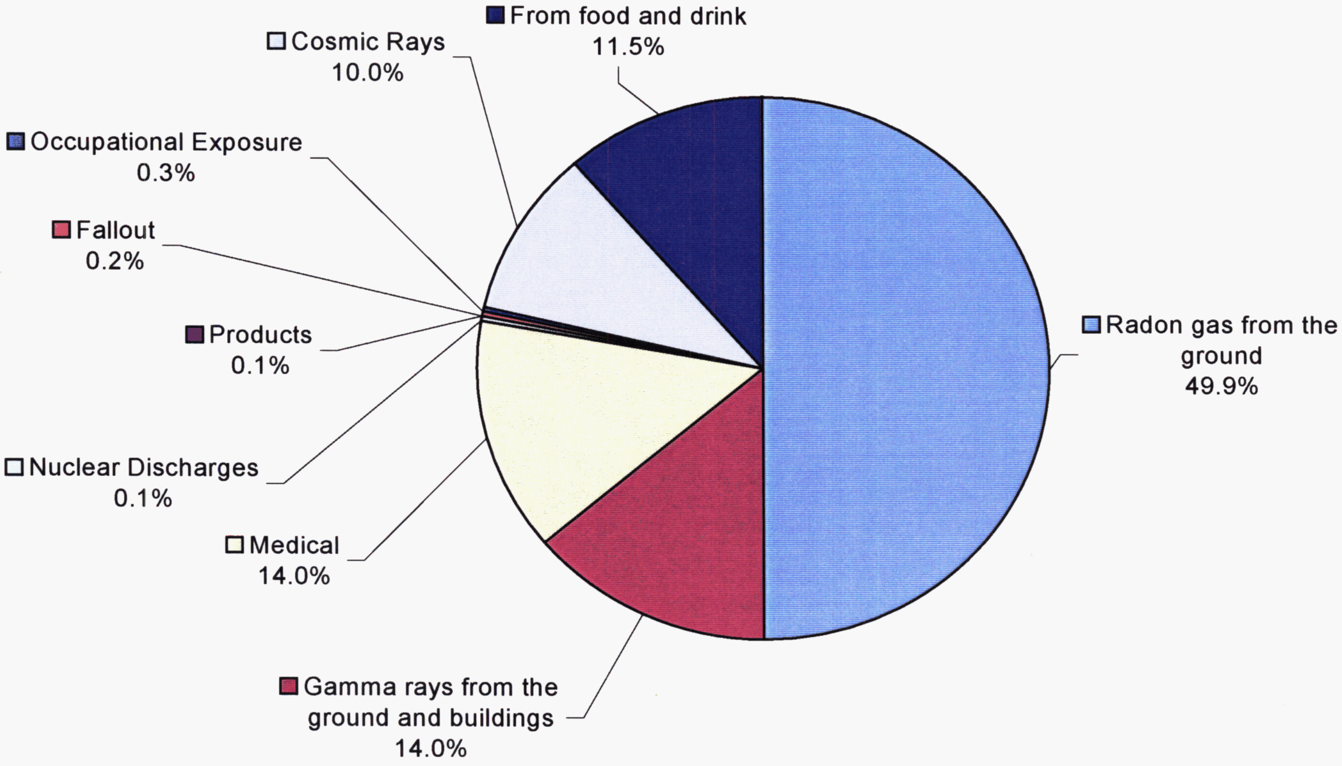

Figure 1.1: Average yearly dose to the UK population from various radiation sources (average 2.6 millisieverts)

2. HISTORICAL AND CURRENT UK USE OF RADIOACTIVE MATERIALS

2.1 Introduction

Since the Industrial Revolution, increasing quantities of radioactive substances have been produced, used and disposed of in various ways. Radioactive materials present a risk in terms of longevity and a legacy of poor disposal practices owing to lack of understanding of their true hazard. Following the discovery of the "Uranic Rays" by Henri Becquerel, and polonium and radium by Pierre and Marie Curie, both in the latter years of the last century (Institut Curie, 1999), radioactive materials have been used in a wide variety of applications, from beneficial medical treatment, to industrial and military uses. As the study of the new science matured, the nature of and risk associated with radioactive material was quantified, and applications and disposal practices which had previously been generally accepted were modified or abandoned completely. Accordingly, although many continuing practices were modified, sites which had been contaminated from former practices remained.

2.2 Use of Radioisotopes

Radioactive materials generally exist in two forms, those which are naturally occurring, and which could have been artificially enhanced, and those which have been artificially produced in a nuclear reaction process from naturally occurring materials. Naturally occurring materials are either utilised in their natural state, or refined to produce greater concentrations of the desired element. Artificial materials are produced from refined natural materials, for example uranium-238, in a reactor where neutron bombardment will stimulate transmutation into the desired element, such as plutonium and its daughter product, americium.

Naturally occurring ores containing radioactive materials are extracted over a wide geographical distribution, and principally include monazite sand, pitchblende, phosphatic rock and pyrochlore (Goodall, (1957), NRPB, (1996)), while uranium is further refined in this country from an already concentrated ore, known as 'yellowcake'. As a consequence of the refinery process, waste streams containing elevated natural radioisotope concentrations were often accumulated on refinery sites (NRPB, 1996).

The UK situation is dissimilar to other major international occurrences of contamination, as this country has none of the large-scale problem contaminated sites associated with uranium extraction, under-regulated nuclear activities and weapons testing. The Licensed Nuclear Industry use of radioisotopes is excluded from this summary, as the current regulatory framework allows their control through the Nuclear Installations Act. Any potential contamination issues on a licensed site will need to be dealt with as a matter of course prior to the de-licensing of that facility, as this process cannot be completed until there is "no danger" from radioactivity.

Uses of radioisotopes were, and still are, widespread and numerous. An overview of the different uses is given in Table 2.1 and, although some of these are not thought to have taken place in the UK, their inclusion is important for the general context:

Table 2.1 Summary of the uses of radioactive materials

Use	Associated radioisotope
Luminising	radium-226, tritium (H-3), promethium-147
Beta lights	tritium, promethium-147, americium-241, thorium
Cold cathode doping and ionising	tritium, radium
Gas mantle production	thorium, cerium
Phosphate fertiliser	uranium-234,238, radium-226, 228, lead-210, thorium-228, 230, 232
General mining and extractive industries	uranium, thorium-232, radium
Precision measurement and gauging, thickness gauges, package filling monitors	strontium-90, krypton-85, promethium-147, caesium-137, americium-241, thorium-204, ruthenium-106, cerium-144, carbon-14, sulphur-35, thulium-169, iridium-192, cobalt-60
Instrument calibration and testing	plutonium-239, americium-241, curium-244, neptunium-237, protoactinium-231, californium-252, iron-55, nickel-63
Static elimination	thorium-204, polonium-210
Smoke detectors	americium-241
Lightning conduction	radium
Radiotracers - general	sodium-24, gallium-72, radon-222, phosphorous-32, caesium-134, iodine-131, carbon-14
Radiotracers - medical	iodine-131, iron-59, cobalt-57/58, gold-198, iodine-131, sodium-24, phosphorous-32, bromine-82, potassium-42
Sterilisation	cobalt-60, caesium-137
Gamma radiography	radium, cobalt-60, iridium-192, caesium-137, thulium-170, ytterbium-169
Radiotherapy	radium, radon, tantalum, gold, caesium-137
Processing of metal ores	
- tin slag	polonium-210, uranium-238, thorium-232
- niobium	cerium, ytterbium
Refined metals technology (including Depleted Uranium applications)	thorium-228/233 (in magnesium alloys, thoria ware, gas mantles and tungsten wire), uranium-234/238 (catalysts and DU applications), thorium-234, protoactinium-234, bismuth-210
General electronics technology	radium, tritium
Small users (includes hospitals, universities and laboratories)	iodine-131, phosphorous-32, sodium-24, potassium-42, bromine-82, sulphur-35, gold-198
Miscellaneous	caesium (nuclear weapons tests fallout), uranyl compounds (laboratory use)

Luminised instruments and "beta light" sources: paint containing between 5 and 12 micro-Curies radium (185 kBq to 444 kBq) per gramme of paint (HMSO, 1971) was used as a luminescent compound on the dials of instruments to facilitate reading in poor or absent light conditions. Latterly, radium was replaced with tritium and promethium-147. The use of radium-226 for this purpose is widely documented, while Goodall (1957), suggests the use of strontium-90 for a similar purpose. The Luminising Regulations (1947) registered 37 factories by the early 1950s, including 11 Royal Electrical and Mechanical Engineers' (R.E.M.E.) workshops and 3 Royal Navy workshops. There were also thought to be somewhere in the region of 50 luminescent radium users of luminous powder or paint manufactured by one firm, with small amounts of the same being imported from Germany and Switzerland (HMSO, 1971). Goodall (1957) details some 135 factories performing luminising operations at the industries' peak during the Second World War. The raw materials were sourced from Messrs. Broadhursts in Reading, who subsequently moved to a site in High Wycombe. CIRIA (1996) and IRR (1985) document the use of radium, tritium and promethium-147 for luminescent purposes, while Statutory Instrument (SI) 1985 No 1047 defines and exempts gaseous tritium light devices under certain activity thresholds from RSA 1993, and imposes controls on their movement and disposal. Pochin (1983) details a number of radioisotopes used in "Beta Light" sources, including tritium, promethium-147, americium-241 and thorium used in vapour discharge fluorescent lamps.

Cold cathode doping and ionising: tritium was used in gaseous form to ionise cathode tubes, as were compounds of radium and bromine (Goodall, 1957).

Gas mantle production: thorium was used as an enhancer in gas mantles to 'increase' the intensity of light emitted. Although not thought to have been subject to peer review, Mitchell *et al* (1999), documents the decommissioning of a Welsbach gas mantle factory in New Jersey, USA. This facility operated from the early part of this century to the 1940s, when widespread acceptance of electrical light reduced the use of gas lighting. Gas mantle production involved the knitting of a cotton/silk base fabric, subsequently saturated in a solution containing thorium and cerium salts and dried over a form. Columbia University (1993) confirms this with a reference to the "Welsbach mantle", incorporating thorium oxide. In the UK, approximately 5 companies were understood to have manufactured gas mantles, and SI (1962) No 2710 unconditionally exempts the sale and use (but not the manufacture of) thorium incandescent gas mantles from control under RSA 93. Potential contamination is therefore more likely to be associated with the raw thorium feedstock and the process and handling of this material, as the exemption for the mantles themselves was more likely to have been introduced due to the impracticality of enforcement and the minimal risk from the disposal of used mantles.

Phosphate fertiliser and compound manufacture: importation and physical processing of phosphatic rock, which contains elevated levels of uranium oxide from the introduction of uranium by ionic substitution in carbonate-fluoro apatite crystals during their sedimentation in marine environments (Baetsle, 1993). The phosphatic rock is then chemically treated using alkali to precipitate phosphate from the impure phosphatic acid (SI 1963 No 1836). There is an alternative process through which phosphate rock is digested in sulphuric acid to produce phosphoric acid and a waste sludge, (a "wet phosphoric acid process"; Baetsle, 1993). The acid is then reacted with further phosphate rock to produce "triple super phosphate"; most of the uranium is entrained in these fertilisers. Elemental phosphorus is produced from coke in an electric arc furnace, leaving elevated uranium concentrations in the waste slag. A potential waste product from the phosphate production process is phosphorous slag (CIRIA, 1995), or phosphogypsum tailings (IAEA (1997), while the potential exists for wastes to have been generated from the original phosphatic rock extraction. In addition, Stearn (1993) details radium as a by-product of the production of "super phosphate" fertilisers. Baetsle (1993) mentions that the volumes of waste generated are very large, in the region of 100 Mt of phosphogypsum per year worldwide. Bradley (1993) details a number of reports studying concentrations of radium-226 in phosphatic rock, ranging from 30 to 1600 Bq/kg. Penfold *et al*, (1997) states that the 1993 total fertiliser production in Europe (12 member states) was 2.2 million tonnes, with a number of radioisotopes including uranium-238, uranium-234, thorium-230, radium-226, lead-210, thorium-228, radium-228, thorium-232 present in the fertiliser. It is not known what the quantities of materials handled in the UK are, although NERC (1994) quotes 1993 imports of phosphatic rock to be 42169 tonnes and exports to be 67 tonnes. Considerable quantities of other phosphatic substances are also imported, including ammonium phosphate fertiliser, superphosphates, calcium- phosphate, sodium-phosphate and ortho-phosphate, all of which have a marked balance of trade to their importation.

General mining and extractive industries: Wichterey (1993) details the history and extent of copper smelting operations in central Germany, which, over many years, have resulted in elevated levels of radioactivity, chiefly due to the presence of uranium (as uranite and uranopilite) and its progeny. The uranium mill tailings problem is well documented, with an EPA project dedicated to the gradual remediation of such sites in the USA (Gonzales *et* al, 1994, IAEA, 1997, Frost, 1998). An example of the quantities of material involved is given in NEA (1997), which states that Canada has generated approximately 200 mt of uranium and associated tailings since 1950. Such sites are not likely to be encountered in the UK (Barraclough, 1997), although sites associated with the refining of uranium, such as the original Springfields plant, are located in this country. This latter plant may have received relatively impure feedstock in the 1950s, with relatively high radium concentrations, but this material is understood to have been removed from site some time ago. Small quantities of radioactive material can also arise as by-products of an established process, for example elevated levels of radioactivity have been observed on North Sea drilling stems and bits, thought to be due to a coating of fine rock powder. This material is termed Low Specific Activity (LSA) Scale. A similar fine material is entrained in the North Sea extracted natural gas stream, and is trapped out upon reception onshore (Entec, 1997). The refinement of thorium from monazite sands can produce a radioactive waste residue (CIRIA, 1996, Drury, 1995, Strearn, 1993), or otherwise contaminate the environment in which it is processed. Thorium-232 is present in monazite sands in activity concentrations ranging from 100 kBq kg^{-1} to 900 kBq kg^{-1} (Hughes and Shaw, 1996), and has been refined from monazite in at least two facilities in the UK (Drury, 1995, Stearn, 1996), one of which also processed radium, and the other of which also processed cerium. Radium can be produced from carnotite sands (Anon, 1997), although was originally produced from pitchblende, and was commercially available as bromide or chloride. Penfold *et al* (1997) mentions the extraction of zircon from zircon sands, which also include monazite and bastnaesite, used in the production of refractory materials, as well as in fine ceramics and as an additive. Exposure pathways include the inhalation of dusts created in extraction and product finishing activities, and external irradiation from stockpiles of the materials. Rare earth extraction from monazite and bastnaesite will also result in a waste stream of elevated radioactivity. In Drury (1995), the remediation of a factory processing and handling radium, thorium and monazite was reported, historically radium and thorium were deposited on site in an uncontrolled manner.

Precision measurement and gauging: radioactive materials can be used in a wide variety of applications in this area. These include thickness gauges incorporating strontium-90, krypton-85, promethium-147, and portable gauges incorporating caesium-137 and americium-241. Other applications which can utilise radioisotopes include machine wear measurement, measurement of the volume of, for example, coal passing over a conveyor and borehole geophysical logging, while more miscellaneous uses include liquid level controls and package filling monitors (Goodall, 1957). This source also documents the use of foil or sealed capsule gauges including thallium-204, strontium-90, ruthenium-106, cerium-144, promethium-147, carbon-14, sulphur-35, thulium-169, iridium-192, cobalt-60) to measure the thickness of plastic, rubber, linoneum, sheet steel, aluminium, copper, brass, cardboard and tissue paper. With respect to waste disposal, the source mentions that "... problems of disposal of spent material have not yet arisen on any scale", going on to recommend the formation of a policy on the disposal of these materials as they were a comparatively recent innovation in 1957. NRPB (1997) describe precautions to be taken when storing, using and transporting nuclear moisture density gauges. Incorporating two sealed sources, caesium-137 (gamma) and americium-241/beryllium (neutron), these gauges can be used to measure density and moisture properties of bulk laid materials, such as roads. All sources used for measurement and gauging are of a sealed, or cohesive, nature, and may be of short half life in which case the hazard associated with older "lost" sealed sources is low.

Instrument calibration and testing: the current production of radioisotopes for this purpose includes plutonium-239, americium-241, curium-244 and neptunium-237 for alpha spectrometry, actinide tracer solutions incorporating some 25 different radioisotopes including protactinium-231 and californium-252 and gamma reference sources, detailed in the QSA internet web site (QSA, 1998). "QSA Ltd." is the long established supplier of radioactive material in the UK, and was formerly part of Amersham International, which itself was formerly the Radiochemical Centre. SI (1985) No 1049 defines sources as homogeneous, laminated, sealed, electrodeposited or tritium foil sources, and mentions electrodeposited sources as those that feature surface deposition of iron-55 or nickel-63. Again, most sources are in a cohesive form, and may incorporate short half life radioisotopes. Historically, the extent of use of such materials is unclear, as the major information sources are fairly modern.

Static Elimination: QSA (1998) details passive, electrical and radioactive products for the control of electrostatic charge, specifically aimed at paint spraying and converting applications, although it mentions that electrostatic charge can generally be a disadvantage to many industrial processes. Foils and brushes for static elimination are detailed in Goodall (1957), and were produced in the UK by Harwell and Amersham, and supplied by two firms; Ekco Ltd and Isotope Developments Ltd. One version was known as the "Ionoton Static Eliminator", imported from the USA. HMSO (1971) mentions the use of thallium-204 for static elimination. These materials are thought to have been supplied in a cohesive form although, for example, some degree of dispersibility would have been associated with items containing brush filaments. Another isotope used for this purpose is polonium-210, which is a relatively short-lived isotope.

Smoke detectors: the alpha emitter, americium-241, is used in a solid form to measure atmospheric alpha-particle absorbance, used for smoke detection. Goodall (1957) includes smoke and fire detection as a use of sealed radioactive sources, including radium foil. The RMRT Regulations (1996) exclude the transport of >500 smoke detectors, each of <40KBq, while SI (1980) No 953 exempts smoke detectors which are radioactive solely due to the presence of americium-241 with a specific activity. The americium-241 source is a discrete cohesive mass of material, although disposal of such sources to landfills, and subsequent compaction and potential for rupture, may result in the dispersal of these sources.

Lightning Conductors: SI No 1835 (1963) refers to the incorporation of radioisotopes into lightning conductors. The materials were incorporated into the "air termination", or the tip of the conductor used to discharge or collect charge, of lightning conductors and "other building protection devices". Radium, and subsequently americium, were used for this purpose. It is thought that a lightning strike to the conductor could result in the dispersion of some of the material. The SI is now revoked.

Radiotracing: the use of several, comparatively short lived, isotopes for radiotracing pathways through various media. These isotopes included sodium-24, gallium-72, radon-222, phosporous-32, caesium-134, iodine-131 (Goodall, 1957), which also mentions the use of the longer lived carbon-14 radioisotope. Wilson (1966) details a number of radiopharmaceutical applications which divide into the use for examining body composition, physical tracing, isotopic tracing (e.g. iodine-131, and intestinal absorption of iron-59, cobalt-57/58) and scanning techniques. HMSO (1971) mentions that a number of radioisotopes are likely to have been discharged in liquid effluent form from hospitals, including gold-198, iodine-131, sodium-24, phosporous-32, bromine-82, potassium-42, although these are all fairly short-lived nuclides. Consequently, although easily dispersible, the effects of these radioisotopes will be fairly short-lived.

Sterilisation: Radioactive material is used for sterilisation in medical and foodstuff processes. Pochin (1983) mentions that gamma radiation may be used in the sterilisation of foodstuffs and medical supplies, utilising cobalt-60 and caesium-137. It is understood that residual radioactivity is not a problem with irradiated materials. The potential for contamination from this application is low, given that it is a relatively recent innovation.

Gamma Radiography (medical and industrial uses): the use of radioisotopes to enable the non-destructive internal imaging of either biological matter or industrial products. Goodall (1957) details the use of "radium bombs" for gamma radiography of castings, welds and fabrications in around 10 factories, which by the end of 1956 had reduced to 1 factory, with the advent of man made isotopes. The spent radium "seeds" were returned to the Radiochemical Centre, Amersham, while the state of the art in 1957 appeared to be the use of cobalt-60, iridium-192, caesium-137, thulium-170 with source strengths from 8.5Ci (3.145 GBq) for cobalt-60 and 18Ci (666 GBq) for iridium-192. The cobalt, iridium and thulium were sourced from Harwell, and returned thence following use for re-irradiation. QSA (1998) details current materials and practices in the non-destructive testing industry, including radiographic sources and equipment. HMSO (1971) mentions that around 370 factories have been supplied with sealed sources for radiography, mainly iridium-192. Industrial radiography uses comprise the production of radiographs using x-ray-generating equipment, or by using a temporarily exposed source aligned with the film and object to be radiographed. Radioisotopes used as radioactive emitters include cobalt-60, caesium-137, iridium-192, ytterbium-169, thulium-170 (NRPB, 1992), in solid form, although older uses occasionally used dispersible forms of material within a container, particularly in medical applications. The main issue with radiography sources is that they are usually of very intense activity, and so the consequences of uncontrolled exposure can be undesirable.

Radiotherapy: Radiotherapy as a branch of medicine was stimulated by the establishment of the Radium Institute by the University of Paris and the Pasteur Institute, in 1909, comprising two divisions; a physics/chemistry branch and a biological and medical branch. This is now the Institut Curie, leading studies in cell biology and cancer research (Institut Curie, 1999). The International X-Ray and Radium Protection Committee, in a report from 1937, document the use of radium salts in radium teletherapy. A container was positioned and adjusted on the patient, into which radium salts were introduced to provide the requisite irradiation. Radium and radon were used, albeit shielded inside sleeves and capsules of stainless steel to prevent direct alpha radiation damage to the dermis, in needles and seeds introduced to the bodily tissues proposed for irradiation (Pochin, 1983). The principle was to apply gamma radiation to the tumours requiring treatment, and these methods of tissue irradiation were later adapted using tantalum or gold nuclide wires instead of radium and radon. X-Rays were also used in this application, although no residual radioactive material or contamination is associated with this method, as the radiation is electrically generated in a cathode ray tube. IAEA (1997) refers to an incident in Brazil in which a 51TBq caesium-137 source was removed from its shielding in a teletherapy machine, located in an abandoned clinic. The source was subsequently ruptured, resulting in radiation doses to workers, and requiring extensive remediation. ARSAC (1998) gives comprehensive details of the specific uses of and conditions treatable with radiopharmaceuticals. Thus, the form and subsequent fate of radioisotopes utilised in medicine vary, with discrete sources, in the form of pelleted material, wires, needles etc, and potentially dispersible sources, including radium salts and other nuclides in a form which can be administered into the body for biological uptake.

Miscellaneous Medical uses: Anon (1998) details several dubious radium "cures" marketed commercially in the past. These include "The Cosmos Bag", incorporating low grade radioactive ore in the fabric, applied to rheumatic and arthritic joints and radium water cures, produced by steeping a radioactive ore mass in water. Radiopharmaceutical plants are cited in Barraclough and McDonnell (1993) as one of a range of non-nuclear sites with potential contamination problems. Stearn (1993) lists a number of processes which, in the early part of this century, may have used radioactive sources in an open form. Amongst these were the production of sealed sources for medical use, "emanators" to produce a dissolved radium drink, and face powder with added radium alleged to improve the complexion.

Processing of Metal Ores:

Tin

In CIRIA (1996), tin extraction is highlighted as posing a source for radioactive materials, while tin smelting slag has been used as bulk fill on development sites. It has been estimated that the quantity of tin slag produced in the north west is in the order of thirty million tonnes. The material is fairly dense and vitreous, lending itself to use as a bulk engineering material, with the result that quantities have been used as railway embankment construction material and hardcore for concrete. This material has been observed as being of detectably elevated radioactivity. The most important ore for tin smelting is cassiterite (SnO_2), while other sulphide ores are also of commercial significance, including stannite (Cu_2FeSnS_2) and tealite ($PbZnSnS_2$). Radioisotopes associated with tin ore and slag include polonium-210, uranium-238 and the thorium-232 decay chain (Penfold *et al*, 1997).

Niobium

Niobium is resistant to corrosion, and consequently is used in a wide variety of applications including electrical components, chemical engineering, in nuclear reactors and in aerospace. It is refined from, among others, tantalite ($Ta_2O_6(FeMn)$), columbite (Nb_2O_6Fe), fergusonite

($(NbTa)O_4(YerCe).Nb_2O_7Ca_2$) and pyrochlore ($(Na, Ca, Ce)_2Nb_2O_6F$) (Penfold et al, 1997). NERC (1995) details the 1993 import of niobium/tantalum ores and concentrates as 322 tonnes, with no associated export. The potential problems associated with the processing of these ores include the elements cerium and ytterbium. The ores are contaminated with traces of uranium and thorium.

Other Metals

Penfold et al (1997), include the following metals as potentially raising radiological issues in their extraction from ore: aluminium, copper, iron and steel, zinc, molybdenum, vanadium, hafnium, zirconium.

Refined Metals technology: thorium is included in magnesium-thorium alloys used in the aircraft industry, at 0.75% concentrations in tungsten wire, as a "getter" in vacuum tubes, in high temperature catalysts, and as thorium chloride in incandescent lighting. SI (1962) No 2648 exempts lighter flints incorporating "Schedule 3" (of the RSA 1960, and thus the subsequent Schedule One RSA 1993) elements. SI (1962) No 2710 defines hardener alloys as magnesium alloys containing <4% thorium, and describes "Thoria ware" as fired ceramic and refractory articles containing thorium oxide. Thoriated tungsten is also described as containing <4% of thorium as an alloy. Thorium was used in its oxide form in mantles for incandescent lighting, and can also emerge as a slag from some metallurgical processes (Stearn, 1993). CIRIA (1996) outlines a number of industry profiles, such as metal processing of light alloys for use in jet aircraft including thorium-228, thorium-233, radium-228, and by-products of the uranium depletion process used in the production of shielding against ionising radiation, aircraft control surface counterbalances and ordnance, including uranium-238, uranium-234, thorium-234, protactinium-234 and bismuth-210. Uranium alloys can be used as catalysts (Tothill and Tuck, 1998). Uranium has also been used in catalysts for chemical reactions, and has been highlighted as being present on some gasworks sites.

Depleted Uranium

A specified case of refined metal usage is that of Depleted Uranium (DU). Natural uranium is processed to separate the fissile U-235 isotope, which constitutes around 0.7% w/w of natural uranium, from the much prevalent U-238 isotope. The waste product from this process is often in the form of uranium hexafluoride, and may be further processed to produce DU metal. There are a number of uses of DU, which include aircraft control surface counterweights, where DU is used because of its 65% greater mass than lead, radiation shielding for medical radiography applications, particularly where cobalt sources are concerned, and in ordnance. perhaps this latter use is that most widely known. In a recent fire at the Royal Ordnance DU works in Wolverhampton, between 200 and 500 kilograms of DU machining residues oxidised rapidly, structurally destroying the building, and coating the interior surfaces with uranium oxides (Macro, 1999).

General electronics technology: Goodall (1957) states that radium is used for certain valves and "cold cathode" doping, while tritium was used in gaseous form for ionising cold cathode tubes, along with radium bromide in certain radio valves. HMSO (1971) confirms the use of radium bromide in cathodes on valves, and also mentions the use of radium sulphate in self-starter switches. Goodall also mentions that there were (in 1957) numerous research departments and laboratories of factories using and producing radioisotopes, and raises the issue of the fate of waste arisings from these operations. The use of radium compounds in valves is also documented, with the use of radium sulphate and radium bromide, the general supply of foils of radium/silver, radium bromide solution, clinical sources and luminescent paint/powder used by scientific, electronic and some engineering/research associations. As this reference is fairly old, it may be assumed that some *ad hoc* disposal of these substances took place in the vicinity of buildings used for these purposes, down drains and so on.

Small Users: HMSO (1971) mentions the use of iodine-131, phosphorus-32, sodium-24, potassium-42, bromine-82, sulphur-35 and gold-198 for medical and teaching applications. In McDonnell, (1996), the small users group includes universities, hospitals and laboratories, from which liquid discharges of radioisotopes occur to sewage treatment works, while atmospheric discharges take place through stack emissions.

Miscellaneous: The Ministry of Aviation highlighted a potential issue arising from radioactive material in a 1966 report. Aircraft travelling in the stratosphere collect dust, some of which is radioactive from past nuclear weapons tests. This can accumulate on various parts of aircraft, for example engine compressor fans and control surfaces, and could present a potential hazard upon maintenance. In HMSO (1971), uranyl acetate and uranyl nitrate are stated as common laboratory reagents. The Medical Research Council mentions a very specific use of radioisotopes in X-Ray Fluoroscopy for shoe fitting, although the practice was seen as largely going out of use in the 1959 report.

A large number of these applications are still current at the present time. A general comment on industries that have used or continue to use discrete sources (for example for gamma radiography) is that, while the sources are now closely controlled, this may not have always been the case. Consequently, the likelihood exists for these sources to have been disposed of on sites where they have been used in an *ad hoc* manner. The Ciudad Juarez incident in 1983, where a cobalt-60 source was dismantled and partially included in the scrap stream, highlights the effect of uncontrolled activities affecting radioactive sources (Brown *et al*, 1996).

2.3 Principal Potentially Contaminated Sites

With reference to the above breakdown of radioactive materials use, the principal potentially contaminated sites that could be encountered in the UK are fairly comprehensively outlined in CIRIA (1996), which highlights a number of different site uses from which the principal hazards are likely to be radiological. These, with additions from other sources, are summarised below, for which they have been divided into sites of lower and higher hazard potential. Nuclear "Licensed Sites" are excluded from this study as detailed in DETR (1998): "The proposed regime for radioactively contaminated land will not apply to users or sites that are already subject to regulation under the Nuclear Installations Act, since such sites cannot be de-licensed until there is no danger from radioactivity on the site. This study is directed towards the ICRP "Intervention" case, where areas of high occupation, for example residential housing and offices, may have been unknowingly developed on areas contaminated by former processes.

Potentially contaminated sites can be qualitatively divided into two sets of case, the "higher contamination potential" sites being those where the land use profile suggests a strong likelihood of there being contamination present, such as with old luminising works and former rare earth works. A second class is the sites where a limited quantity or severity of contamination is possibly present, or those of "lower contamination potential". Figure 2.1 shows the various industrial uses of potential contaminants, in most cases, potential for contamination arises following the use of the material.

2.3.1 Sites of Higher Contamination Potential

- MOD: "MOD" sites can comprise a variety of land uses ranging from sites with a low potential for contamination such as barracks through to operational maintenance and repair facilities with a higher potential for contamination. The historical use and disposal of materials, sometimes in an uncontrolled manner has been one of the main causes of contamination on occupied sites. Gibbs (1993) describes historical radioactive contamination at MOD sites to mainly comprise radium contamination from old luminising operations and equipment. For security (and possibly volumetric reduction) reasons, redundant equipment was routinely incinerated, and often the ashes were disposed of upon the site around the incineration areas. In addition, luminising workshops, storage facilities and disposal areas can contain contamination, in the form of paint vials, discrete particles of luminous paint, fragments of instrument and other substrate upon which the radioisotopes have been in contact. In some cases, instrument dials have been disposed of directly to areas surrounding maintenance facilities. Other less significant sources of radioactive contamination on military sites include betalights, electronic valves and sealed radioactive sources used in Non Destructive Testing and instrument calibration. In the past unsealed radioactive sources were used in training exercises. It has been stated that materials with half lives less than 12 days were used and should therefore be of negligible significance today. Exercises were followed up by thorough decontamination.

- Munitions manufacture: CIRIA (1996) highlights isotopes from depleted uranium - uranium-238, uranium-234, thorium-234, protactinium-234 and bismuth-210 to be associated with this land use. Depleted uranium is often used, owing to its mass, in projectiles and aircraft control surface counterweights.

- Mining and extractive industries: This includes mining for uranium, radium and tin, radon pathways in old mineworkings, extracting materials of elevated uranium and thorium concentrations). Although large scale extraction of ores to produce radioisotopes is thought not have taken place in this country, it is understood that importation of such ores and subsequent processing did take place (Stearn, 1995 and 1996, Drury, 1995, Barraclough, 1997). In particular, Stearn (1995), outlines the potential problems encountered during the investigation of a rare earth works handling monazite sands, which can contain up to 10% thorium in enriched forms (HMSO, 1971). A particular type of contamination exists in the Northwest of England where a past history of tin smelting in the area has resulted in large quantities of tin slag. The amount produced has been estimated to have been in the order of thirty million tonnes and, owing to good engineering properties, the material has been used extensively as aggregate for railway embankments and general civil engineering, before the potential radiological hazard was appreciated.

- The Phosphate Industry: This industry is understood to process ores in this country (CIRIA, 1996), and elevated levels of uranium-238 daughters are found in the waste streams of this process.

- Metal processing and refining industries: Principal isotopes of concern include thorium-228, thorium-233, radium-228 from the manufacture of light alloys for use in jet aircraft and uranium-238, uranium-234, thorium-234, protoactinium-234, bismuth-210 present as by-products of the uranium enrichment process, used in production of aircraft counterbalances and shielding against ionising radiation. The past and present refinement of radium, thorium, depleted uranium (DU), protactinium and bismuth-210 can result in the creation of waste slags (CIRIA, 1996). Also, the historical processing of copper and tin

(Wichterey, 1993, Sutherland, 1999) has resulted in extensive contamination of areas contaminated with waste and radioisotope tramp elements.

- Gasworks: Uranium catalysts are suspected to have been used at some sites (Tothill and Tuck, 1998) and the concentration of lead - 210 in pipework has been reported. As coal carbonisation involved the destructive anoxic distillation of coal, the ash residues of such a process will contain elevated levels of natural radioisotopes, including uranium, thorium and radium, enhanced from their natural inclusion into the feedstream.

- Landfill sites: The Sitefile Digest (Landmark Information Group Ltd, 1999) details all authorised waste disposal sites in the country, should data on licensed waste types be required. Prior to the Control of Pollution Act (1974), there was no structured regulation of waste material accepted by a site, with some types of material "permitted" on a Planning Basis. Landfills filled and completed prior to regulation with no records of the quantities and types of materials tipped, may have had radioisotopes tipped along with other waste types. The Environment Agency Monitoring Report for 1996 (EA, 1999) gives tritium and gross beta monitoring data for surface and groundwaters in the vicinity of a number of landfill sites, some of which have received Special Precautions Burial wastes and Gaseous Tritium Light Devices (GTLDs). Some sampled media, for example landfill leachates from within the fill, have tritium concentrations in the range of 10^2 Becquerels per kilogram, which highlights the ready mobility of tritium.

- Luminising works: Drury (1995) details the investigation and remediation of a luminising works, which was subject to contamination by radium, thorium and rare earth salts. Other sources (Goodall, 1957, CIRIA, 1996, SI (1985) No 1047) include promethium-147, tritium and strontium-90 within the scope of luminising operations. It is also thought that a consequence of the Luminising Regulations meant that "kits" of the relevant materials were supplied to both industry and individuals, and a slight possibility exists for ad-hoc disposal of paints, containers and application materials to have taken place on both recognised sites and workers' domestic properties.

- Cottage Luminising Industry: There have been a number of cases reported of individuals operating luminising workshops from their private residences (Goodall, 1957). These workshops would have used radium paints, with poor working practices and waste disposal methods being a likely feature of such work. It is therefore possible that these residences have areas of contaminated land and contaminated drainage and buildings structures.

- Gas mantle manufacturers: HMSO (1971) mentions the process behind gas mantle production, in particular the precipitation of thorium salts in solution onto the mantle substrate.

- Instrument makers:. radium-226 from luminising operations is particularly important and might be present in both small-scale and large-scale production facilities

2.3.2 Sites of Lower Contamination Potential

- Non-ferrous metal smelters: (e.g. tin, niobium, aluminium, etc). Potential contaminants include the enhancement of naturally occurring uranium series isotopes into slag residues;

- Coal fired power stations: An issue can arise from the natural inclusion of uranium, radium and thorium in coal and the subsequent concentrating entrainment of these substances into fly ash and slag following combustion (UNSCEAR, 1977);

- Shipbreaking sites: Use and disposal of radium luminised instruments;
- Chemical plants: depends on process types, uranium has been used as a catalyst (Tothill and Tuck, 1998);
- Incinerators: These can be subject to contamination with various radioisotopes, the precise character of which is dependent on feedstream;
- Sewage treatment works: Potential radioisotopes present is dependent on the trade effluent accepted, especially if the works is the destination of effluents from "Small Users" such as universities, hospitals and laboratories;
- Scrapyards: Disposal of items incorporating luminised instruments (radium-226, promethium-147, tritium), irradiated items and contaminated articles. Woollatt (1999) and Macro (1999);
- Industrial processes and applications: Once refined from the ore mass, further processing may take place to produce a product which is commercially useful. For example, the use of thorium as an intensifier in gas mantles, as a hardener in alloys and in various sundry applications (CIRIA, 1996, Stearn, 1993) or radium as luminising paint (Barraclough and McDonnell, 1993). Consequently, the locations of these processes, the plant and machinery involved in them and any waste products, will represent a source of radioactive contamination. It is also conceivable that, prior to statutory controls over the use, storage and disposal of radioactive materials first introduced through the Radioactive Substances Act (1960), sealed and unsealed radioactive sources may have been disposed of on an ad-hoc basis upon the sites where they were used, or disposed of in an uncontrolled manner to Local Authority facilities;
- Laboratories: As far back as 1957, Goodall raises the question of waste disposal from laboratories, with experimental radioisotopes potentially being entrained with normal effluent and solid waste streams;
- Hospitals and clinics: Older practices of radiography utilised intense radioactive sources. IAEA (1997) details an incident concerning a large source of caesium-137 undergoing decommissioning from an abandoned clinic in Brazil. Wires, needles and dispersible sources of radiation were also utilised, and may have been disposed of improperly;
- Construction industry: The use of the phosphate processing waste product, phosphogypsum, as a form of gypsum for plaster, can allow entrained radioisotopes to present a radiation issue (UNSCEAR, 1977). The tin slag wastes in the northwest (Sutherland, 1999) also highlights the problem where materials are used owing to their beneficial characteristics without further evaluation.

2.3.3 Accidentally Contaminated Sites

There are many literary references to sites outside the UK accidentally contaminated as a result of spillage, malpractice or industrial accident. A particularly good example of this is the Antwerp Conference, from which a number of papers have been reviewed for this study. This conference, held in 1993, dealt with a number of radioactive contamination and restoration situations, the most well-known of which was the Chernobyl incident. A number of papers dealt with the restoration and remediation of areas around Chernobyl, through the location, removal and disposal of radioactive material dispersed by the event, as well as more general controls on the movement of foodstuffs and populations around the area. With respect to accidentally contaminated sites within the UK, many of the papers presented at Antwerp deal with UK sites from the historical contamination perspective, with contamination arising as a result of past operations on the site, as opposed to accidents.

Other types of accident outside the nuclear sector include the Brazilian clinic example cited in IAEA (1997), where a 51TBq caesium-137 source was removed from its shielding in a teletherapy machine. The source was subsequently ruptured, resulting in radiation doses to workers, and requiring extensive remediation through detector-based radioactive particle location and removal. Two papers, Gutierrez *et al* (1993) and Walmod-Larsen (1993) detail the actions carried out following aircraft accidents where the aircraft involved had been carrying nuclear weapons. The first paper dealt with the aftermath of the collision of two aircraft while refuelling over Palomares, Spain, in 1966. The plume of contamination was characterised using alpha proportional detectors, and several techniques employed to containerise, plough in and wash down contaminated soils, vegetation and buildings. Sampling and analysis over the area allowed an approximation of the plutonium inventory and any residual contamination and risk. A similar event over Greenland is detailed in the second paper, with the crash of a B-52 bomber and subsequent localised dispersal of radioactive material over the ice sheet. Alpha characterisation allowed the collection of the radioactive material which had refrozen into a crust upon the ice sheet following a fuel fire. This material was collected up and stored pending spring in a number of large sealed tanks. Following melting, the contaminated water was transported to the USA. Danish scientific expeditions monitor the area, and estimate that approximately 0.5 kg of plutonium-239 was deposited on the seabed. Although specifically dealing with "nuclear" sector radioelements, these studies detail the typical steps undertaken once notification of a radiological emergency situation has occurred.

Brown *et al* (1996) is a review of techniques for remediation to be employed in the UK following an accidental release of radioactive materials. This reference details the following case studies for accidentally contaminated areas:

- Kyshtym accident of 1957, contamination of River Techa and Lake Karachai;
- Palomares accident in 1966 (detailed above);
- Cuidad Juarez accident in 1983 (detailed above);
- Chernobyl reactor accident in 1986;
- Goiania accident in 1987.

None of these accidents occurred in the UK, although the results of the Chernobyl accident were seen in the upland areas of the UK. This study is mainly geared towards accidents in the nuclear sector, and many of the techniques outlined involve the wholesale removal of surface contaminated materials, brought about by high specific activity deposition on their surfaces. However, there is mention of the Brazilian incident, with the selection of a number of techniques for the removal of caesium salts from surfaces, including firehosing roofs, vacuum sweeping, paint stripping and chemical fixation. Other techniques mentioned include polymer fixation, turf harvesting and sandblasting.

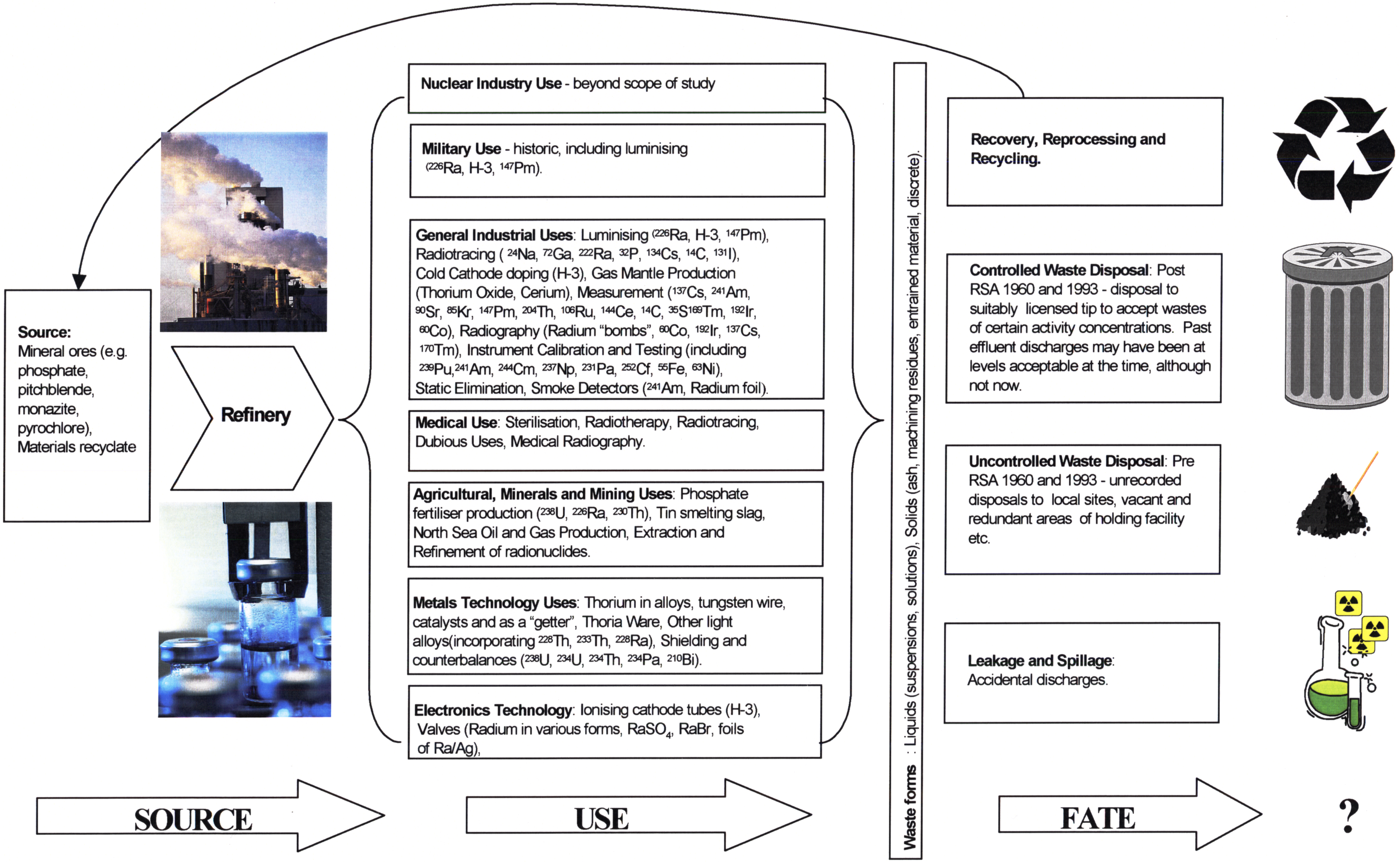

Figure 2.1 Industrial Uses Of Radionuclides

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3. REMEDIATION EXPERIENCE IN THE UK

3.1 Introduction

The breadth of large scale remediation experience in the UK is somewhat limited, as process industries which create large tracts of radioactively contaminated land, such as nuclear weapons testing or uranium milling, have not taken place in this country (Barraclough, 1997). The UK experience has been classified into three main areas: industrial processing (e.g. radium luminising, thorium extraction, minerals processing), Nuclear Installations Act sites no longer required, and areas contaminated, or under threat of contamination, from discharges or disposals at a neighbouring facility.

In general remediation methodologies have simply comprised the identification, segregation and disposal of contaminated materials. There has been minimal application of innovative or emerging technologies such as soil washing, vitrification, etc.

In recent years some preliminary pilot schemes have been conducted of soil washing and phytoremediation on nuclear sites.

3.2 Case Studies

In the United Kingdom, the range of experience of remediating radioactively contaminated sites, has included, in particular, the following situations:

- Military sites contaminated with radium-226;
- Industrial sites contaminated with tin slag containing enhanced concentrations of naturally occurring isotopes;
- Industrial sites contaminated with thorium from gas mantle production;
- Industrial sites contaminated with radioactivity from accidents;
- Public sites contaminated as a result of previous land uses;
- Public sites contaminated as a result of illegal disposals.

Generally, the contaminating processes giving rise to the above occurrences of radioactively contaminated land have resulted in varying volumes of low activity concentrations of radioactive contaminants. However, one important exception is when radium-226 luminised dials have been disposed directly in high numbers within isolated disposal pits. These dials can have activity concentrations greater than 10 kBq/g and, therefore, could be regarded as intermediate level waste and represent a considerable radiological hazard.

The following Case Studies of representative projects detail how radioactive contamination was originally detected, how the distribution of contamination was then characterised, the remediation techniques applied on the site and how the final radiological end point was then confirmed.

3.2.1 Radium 226 and natural uranium contamination at an MOD Site, North West of England

A Land Quality Survey was commissioned by the Agents for a 43 ha ex-MOD Site in the northwest of England prior to intended redevelopment of the site. The site had been used as an aircraft repair and maintenance depot and during the investigation for possible chemical contaminants, suspect artifacts were identified that were subsequently found to be luminised with radium-226 paint. To determine the extent of radium contamination a 100% walkover radiological survey was then undertaken covering the entire site. The survey was performed using 25 mm x 25 mm sodium iodide contamination probes specifically calibrated to respond to radium-226 concentrations. The survey identified elevated concentrations of radioactivity in both discrete areas and individual point sources across the site.

An intrusive survey was then undertaken to establish if contamination extended to depth. This involved approximately 300 trial pits across the 43 hectare site. Trial pits were examined using in-situ probe measurements, and soil samples were collected for gross radioactivity measurements and laboratory analysis by gamma spectroscopy. Analysis of the spectrographic measurements identified that the increased concentrations of radioactivity across the site were due to two separate contaminating sources:

i) Radium-226 contamination associated with the disposal of radium paint residues and from the redundant luminised instruments.

ii) Enhanced levels of natural uranium thought to be associated with imported aggregate fill material, probably derived from a tin smelting process.

The results of the intrusive survey were used to estimate waste volumes and disposal costs, and formulate a remedial action plan.

Since the planned use of the site was for residential purposes the remediation standard was established at the level at which radium-226 is defined as radioactive under the Radioactive Substances Act 1993, that is, 0.37 Bq/g. The remediation standard for natural uranium concentrations was also set at 0.37 Bq/g. Although this concentration is well below the 11.1 Bq/g defined by the Radioactive Substances Act this was deemed desirable due to the sensitivity of the planned residential end use of the site and that 11.1 Bq/g of natural uranium could result in a breach of the 300 μSv/year maximum dose to the general public recommended by the NRPB.

Remediation protocols for the identification, segregation and disposal of contaminated materials were developed to achieve the planned end point. Given the variance in distribution and concentration of the contaminants three averaging volumes were proposed:

i) Removal of point sources (when retrievable);

ii) Digger bucket, approximately 0.5 m^3;

iii) A landfill skip, approximately 10 m^3.

The optimum averaging volume would be selected after assessing all variables by the Site Manager to achieve safe, cost effective remediation of discrete areas of the site.

Wastes were sentenced using 50 mm by 50 mm (2" x 2") sodium iodide probes and confirmatory radiochemical analysis and were consigned from the site to the following disposal routes:

i) Wastes of radium-226 concentration greater than 4.9 Bq/g were consigned for disposal to BNFL Drigg.

ii) Wastes of radium-226 concentration of between 0.37 Bq/g and 4.9 Bq/g were consigned to landfill under the Phosphatic Substances Exemption Order.

iii) Wastes of natural uranium concentration between 0.37 Bq/g and 11.1 Bq/g were consigned to landfill.

iv) All materials of activity concentration of less than 0.37 Bq/g were returned to site as free release.

All wastes were retrieved from site using the above protocols with comprehensive records of consignments being maintained. Further explanation of the methodology behind this approach is given in Section 7, remediation technologies.

Following the completion of waste disposal a validation survey was undertaken. This consisted of a 100% walkover survey and trial pitting at a minimum of 25 m x 25 m grid and a 10 m x 10 m grid in areas previously contaminated with radium-226 point sources.

The site was subsequently re-developed for residential use.

3.2.2 Hillsea Lines, Portsmouth

Originally constituting part of the defensive fortifications of Portsmouth harbour, and formerly used in part by the MOD for luminising operations, the Hillsea Lines site is linear in shape and consists of a number of casements and open areas. The majority of the site was decontaminated in the 1970s by the MOD (Defence Estates), with the exception of a known area of buried very low level radioactively contaminated rubble and soil left on the site with the consent of the Radiochemical Inspectorate. The extent of any remaining contamination and radiological liabilities were assessed during a site survey programme in October 1998. This action confirmed that the majority of the site was free from contamination, with the exception of a number of areas where radium contaminated materials were still found to be present.

The study included an assessment of site geology and hydrogeology and a rationale for further site investigation. It concluded that, from the potential contaminants detailed in historical sources (radium-226, promethium-147, cobalt-60), only radium-226 was likely to still remain at the site. Gamma spectrometry analytical equipment was identified as appropriate for the detection of radium-226, and a site survey was instigated.

A range of equipment was used to undertake a Health Physics survey of the site, including:

- A 1667 beta/gamma scintillation monitor;
- A 44B gamma monitor;
- PAM2 alpha monitor;
- Ludlam low level dose meter;
- Alpha Drawer Counter Series 1300;
- Beta Castle Counting Assay 0653.

A technique for land surveying was utilised to map total gamma activity across the site. This technique featured a Global Positioning System (GPS) combined with a range of radiation monitoring devices to spatially map radioactivity over the site. The majority of the survey was carried out on a 50% areal coverage basis, with selected 95% coverage focused on areas of elevated activity, in particular the low-level waste heaps and the location of the former luminising workshop. Owing to vegetative cover on the site, a 100% survey was not deemed possible.

The GPS was configured to a base station to give a positional accuracy below one metre, combined with a 75 mm by 75 mm Sodium Iodide scintillation detector carried at 0.5 m above the ground surface, so configured to provide a measurement of gamma radiation once every second. This was in turn connected to a Ratemeter which provided gross gamma counts per second to a data logger. The principal problems encountered with this array of equipment were reported as:

- Unless high activities of gamma emitting radioisotopes were present, the detector would only measure through soil to a maximum depth of 0.2 m;
- In certain areas of the site, a full view of the sky was not possible because of buildings and vegetation. This reduced the number of satellites available to the GPS system and generated a ‘ghosting’ effect resulting in a reduced positional accuracy;
- The data were interpolated using an inverse square law relationship over 1-2 m, and the final graphical output reflects this;
- Digital accuracy of OS maps was documented to be +/- 2 m.

Other features surveyed included manholes, to account for any liquid discharges of contamination to sewer, and a pile of concrete blocks which exhibited elevated levels of radioactivity, thought to result from radioisotopes sorbed onto the surface. Alpha, beta, gamma and dose rate surveys were carried out in the area of the casements and buildings, revealing a number of elevated areas of radioactivity of up to twelve times the background level (alpha), although the majority of the readings were well below this intensity.

A number of hotspots were detected using the instrumentation, including an area of elevated dose rates in the vicinity of the gun ramp which itself contained a number of elevated spots. Window sampling and hand dug trial pits were used to explore this area and the general extent of the waste disposal and fill over the site, while other sampling took place of a drainpipe, moat sediments and fruit growing over the site.

Sampling and analysis was performed using a variety of techniques, both field and laboratory based. Field based techniques included the use of health physics instrumentation detailed above, and a portable gamma spectrometer connected to an EG&E Ortec 92X computer system. Laboratory analysis was carried out with germanium gamma ray detectors, while gross alpha and gross beta detection was performed with a Berthold LB770 low-level proportional counter, allowing a minimum detectable activity of 0.1 Bq/g. The sampling and analysis concluded that the area of elevated activity known to have been used as a disposal area for low-level material was overlain with 0.5-0.75 m of capping, beneath which lay materials containing 0.44 to 1.7 Bq/g of radium-226. Several areas were not explored using intrusive techniques.

A Health Risk Assessment was carried out to assess the potential for human exposure through several pathways, including external exposure, inhalation of soil and radon-222 and its progeny, ingestion of soil, wild foods and contaminated water and foodstuffs. External exposure was calculated using an estimated occupancy of the site on a casual basis spent in the vicinity of the contamination, and concluded that the attributable annual effective dose would be 0.075 mSv. The risk of inhalation of re-suspended dust was calculated using a dose geometry relationship to estimate radioisotope concentrations in soil in Bg/g. This data was then used to calculate the annual effective doses from inhalation of radioactive aerosols, resulting in a cautious estimate of total dose. Inhalation of radon-222 gas and its progeny was cautiously assessed to be of potential significance, while ingestion of contaminated soils and wild foods were not seen to be significant.

Principal recommendations for future site management included high priority work, such as removal and disposal of highly radioactive particles, a volume of soil with elevated radioactivity and a piece of active drainpipe, and lower priority actions, which included further investigations and sampling activities. Attention was also drawn to the potential issue of radon-222 inside the locked casements, and the maintenance of the soil cap placed over the low-level material.

3.2.3 Caesium-137 Contamination at a Site in Southwest England

In the early 1990s, a metals smelting operation in the southwest of England commissioned a walkover radiological survey of their site as radiological contamination had been detected on a similar site in the company's international operations. The survey identified a contaminated area of approximately 50 m x 50 m. The company subsequently commissioned a specialist contractor to investigate, characterise and remediate the site. It was discovered that the site had received a batch of metallic feedstock which had become contaminated as a result of the inadvertent disposal and smelting of a Caesium-137 level gauge.

The characterisation of the site was achieved by the implementation of a programme including a walkover radiological survey, core sampling, gross beta / gamma measurement and gamma spectroscopy. This resulted in a three dimensional profile of the distribution of radioactivity across the area and details of the isotopic composition of the radioactive contamination.

The radioactive contaminant was found to be caesium-137. The contractor was able to negotiate the following disposal options, with the relevant regulatory body at the time, which was HMIP:

Activity Concentration	**Disposal Route**
<0.4 Bq g^{-1}	Free release, for backfill upon the site.
>0.4 Bq g^{-1} and <4.0 Bq g^{-1}	Landfill disposal under a Special Precautions Burial Authorisation.
>4.0 Bq g^{-1}	Disposal to BNFL Drigg.

The remediation was achieved by retrieving wastes in 200 litre volumes and sentencing the wastes using direct probe measurements. 25 mm x 25 mm sodium iodide scintillation probes were used that were calibrated to respond to homogeneous concentrations of caesium-137 in the contaminated medium. Calibration factors were applied for both measurements taken directly from the surface of the waste, and for those attenuated through the digger bucket.

The site was remediated to a radiological end point of less than 0.4 Bq/g caesium except in one instance. It was found that some radioactive contamination had migrated beneath a reinforced hard standing into and below the groundwater level on site. It was deemed that this contamination was inaccessible. An estimation was made of the activity of caesium beneath the hard standing and a subsequent risk assessment was undertaken. The risk assessment proved that the contamination posed a negligible risk to site occupants and the general public. Following negotiations with HMIP, the site was capped with a concrete hard standing and the residual contamination was plotted onto site plans to ensure future site occupants were aware of any potential residual risk.

3.2.4 Depleted Uranium at a Fly Tipping Site, Chelveston, Northamptonshire

In 1996 the Environment Agency (HMIP) were alerted to a find of depleted uranium swarf in a scrap yard in Sheffield. An investigation was undertaken which identified that the swarf had been retrieved from a fly tipping site in Chelveston. It was found that drums of depleted uranium had been illegally disposed on the site. Some drums were in poor condition and it was evident that there had been a spread of contamination around the immediate vicinity of the wastes and around the internal roadway used by the fly tippers.

The site was investigated using a 100% coverage walkover survey with large sodium iodide detectors. It was judged that an intrusive investigation was not necessary as the contamination was distributed across the top surface of the site.

A programme of excavation and disposal of contaminated materials was undertaken. Drums of waste were sentenced using surface probe measurements i.e. a 200L litre averaging volume. Drums containing wastes of activity concentration less than 11.1 Bq/g depleted uranium were consigned for landfill disposal. Wastes of activity concentration greater than 11.1 Bq/g were transported for storage awaiting Drigg disposal.

Contaminated soil and concrete were retrieved and stored in landfill skips. Averaged probe measurements were taken across the landfill skips to ensure activity concentrations remained below 11.1 Bq/g and wastes were consigned for landfill disposal.

A validation survey was undertaken and the site was found to be free of residual radioactive contamination.

3.3 Summary of Remediation Experience

From the experience gained in remediating radioactively contaminated sites in the UK to date the following general lessons can be drawn to achieve a high quality remediation.

i) Scoping Investigations and Characterisation Surveys

A comprehensive desk study involving a thorough review of the sites environmental setting, historical activities and operations that could have resulted in contamination and discussions, with site workers (where possible), is critical to successfully scope future intrusive investigations (See Section 4). The study will assist in identifying potential contaminating radioisotopes, the likely concentration of the isotopes, the potential distribution of radioactivity on the site and the potential environmental and human risks that require consideration. This will enable the selection of the most appropriate intrusive and non-intrusive techniques in order to detect both lateral distribution of contamination and buried radioactivity.

Radioactive contamination is often very heterogeneous and, unlike chemical contamination, single point sources can pose an unacceptable risk, a comprehensive approach to investigation is therefore normally required. Fortunately, the nature of radioactivity permits rapid surface walkover surveys to be conducted and the selection of appropriate health physics instrumentation to maximise the effectiveness of such surveys and to identify the radioisotopes of concern is critical. Appropriate laboratory analysis are necessary to 'calibrate' field data to identify the likely range of radioisotopes.

ii) Site Remediation

It is possible during remedial works to create greater human or environmental risks than existed while the material was in situ. It is therefore important that the risks that could occur are thoroughly assessed and detailed protocols to manage and minimise these risks are prepared. The safety of site workers is paramount and should be addressed as part of this assessment. The protocols should also take into account risks to adjacent site users and nearby residents. With respect to the remediation end point this will clearly have to comply with current UK regulation and take account of current UK and international guidance. The future end use of the site should be considered in any risk assessment and the general principle of ALARP (as low as reasonably practical) is often applied.

With respect to waste disposal the definitions within RSA '93 will have to be complied with, at present there is often confusion over the interpretation of the Phosphatic Substances Exemption Order of RSA '93, where scheduled elements are exempt up to activity concentrations of up to 14.8 Bq/g. It is commonly accepted in guidance that this concentration should be divided by a factor of three for radium-226 due to the secular equilibria of its three polonium isotopes. Further explanation of the secular equilibrium issue is given below in Section 6. However, on occasion, wastes containing activity concentrations of up to 14.8 Bq/g of radium-226 have been disposed to landfill sites.

There is also variation in opinion over what constitutes an acceptance averaging volume for the sentencing of wastes. Averaging volumes used in the UK range from a few cubic centimetres to 10 m^3. For example, wastes containing radium-226 point sources have been segregated down to individual dials and artifacts or disposed on bulk for landfill disposal. In order to optimise averaging, it is imperative to consider all legislative guidance to undertake a risk assessment on the distribution of activity within the averaging volume and to consider local conditions and disposal site requirements, as the current legislation does not explicitly specify averaging volumes.

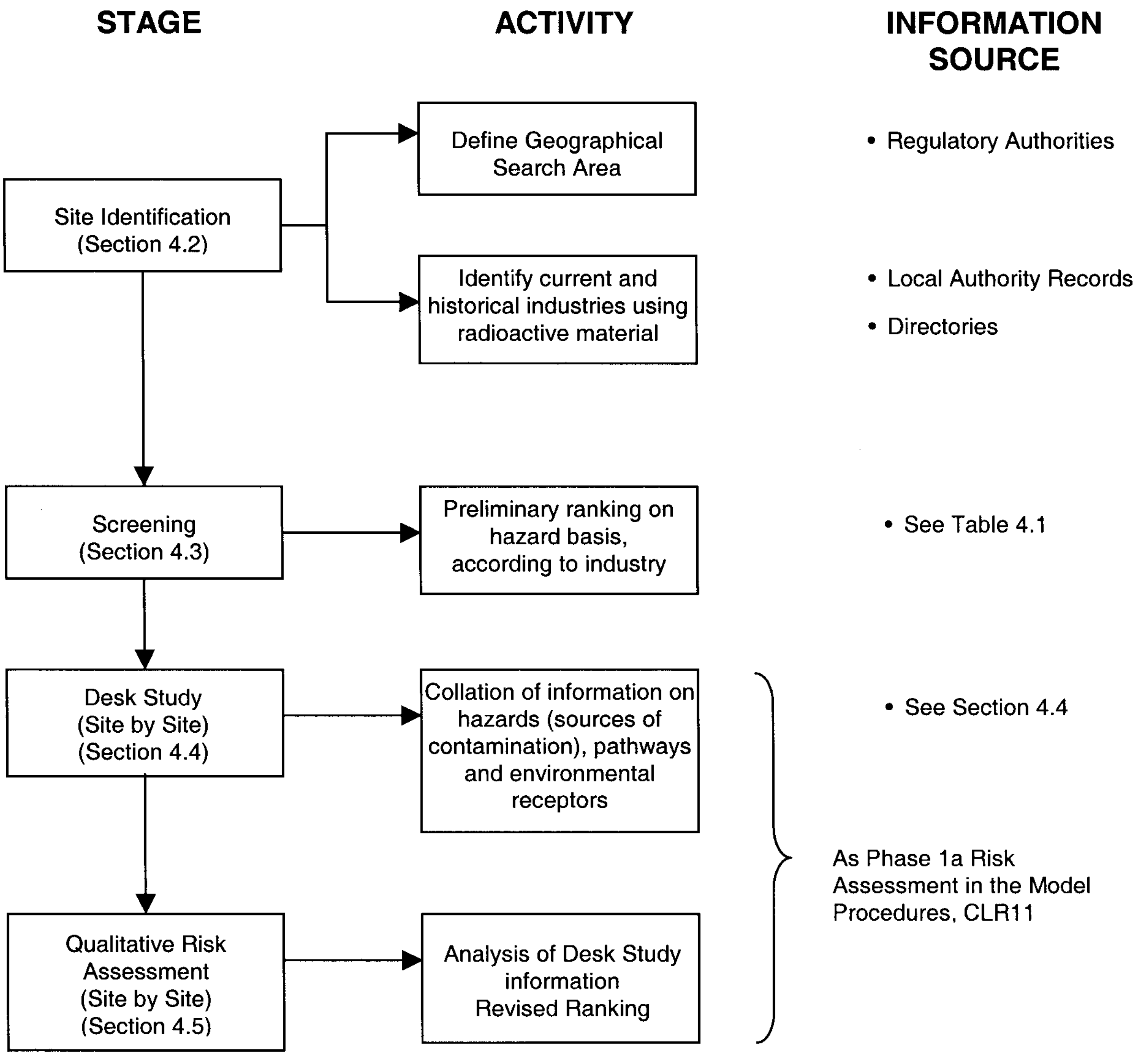
iii) Validation Surveys

To provide confidence in the safety of the site to future site owners and users and to demonstrate that the remediation objectives have been achieved, a thorough validation survey is essential. Similarly the pre-remediation investigation and validation survey should be scoped to detect activity and volumes of any residual radioisotopes.

4. IDENTIFICATION OF POTENTIALLY CONTAMINATED SITES AND RISKS

4.1 Introduction

This Section aims to provide guidance for Regulatory Authorities to assist them in the identification of potentially radioactively contaminated sites on a geographical area basis. It then provides a simple methodology to allow the qualitative assessment of risk on these sites on a basis similar to the guidance. The Section deals with initial actions that may identify such sites, the ranking of a group of identified sites to allow prioritisation, and then the risk assessment process for each site. A summary of this process is given in the flow chart below:



4.1.1 General approach to managing contaminated land

"Model Procedures" for the management of contaminated land (CLR 11) have been developed under the DETR (formerly Department of the Environment) contaminated land research programme and the Environment Agency's Land Quality research programme. They incorporate existing good technical practice, including the use of risk assessment and risk management techniques, into a systematic process for identifying, making decisions about, and taking appropriate action to deal with, contamination, in a way which is consistent with UK policy and legislation. The Model Procedures therefore set out a recommended good practice approach to managing land where contamination is, or may be, an issue.

The Model Procedures approach the contaminated land problem in a hazard and risk management context. The overall process for managing contaminated land is based on a sequence of risk based steps, which fit into a decision support structure. The principal steps are:

i) Risk Assessment;

ii) Evaluation and selection of remedial measures;

iii) Implementation of risk management action.

The Risk Assessment stage is applicable in the context of Tasks four, five and six of this study, and consists of four stages:

- **Phase 1A Risk assessment** = hazard identification: - identification of the contaminant sources, pathways and receptors, or the pollutant linkage, taking into account the actual or intended use of the site and its environmental setting. Actions may include the collation of reference information, a site reconnaissance, including health and safety precautions;
- **Phase 1B Risk Assessment** = hazard assessment: - consideration of the plausibility of pollutant linkages and determination of the potential health and environmental risk;
- **Phase 2 Risk Assessment** = risk estimation: - estimation of risk (s) that identified receptor (s) will suffer adverse effects if they come into contact with, or are otherwise affected by, contaminant sources under defined conditions. Risk estimation involves consideration of the likelihood, nature and extent of exposure (or of other hazardous conditions) and the effects which may occur if exposure takes place, or if hazardous conditions develop. The expression of risk may be in qualitative or quantitative terms;
- **Phase 2 Risk Assessment** = risk evaluation: - evaluation of the need for risk management action (i.e. risk reduction or control measures) having regard to the nature and scale of risk estimates, any uncertainties associated with the assessment process, and, where further action is required, the objectives, broad costs and benefits of that action.

Although principally aimed at chemically contaminated land, the principles and approach of the Model Procedures are also suitable for use for managing radioactively contaminated land.

4.2 Site Identification

Individual authorised sites, operators and industries keeping, using or disposing of radioactive materials are already registered under RSA 1993, and so the details of each operation and the permitted materials are readily available. However, information on sites which historically may have been used for the storage, processing, disposal or use of radioactive materials in the past, and which may no longer be in use, or even may have been redeveloped, is less readily available. A methodology is required to enable the identification of these "invisible" sites on a geographical area basis, to allow a structured programme of radioactively contaminated land identification by responsible bodies, similar to that prescribed for chemically contaminated land.

A research starting point for the discovery of local industries utilising radioactive materials is the local County Archives or Record Offices. These facilities are usually part of the local Library and Museum Service, and contain a wide range of archival material including, but not limited to that outlined below. This information may be prioritised, in terms of reliability, accuracy, coverage and value using the method outlined in DOE (1994c), which proposes a structured approach to information gathering, consisting of the collection and analysis of "Principal" and "Supplementary" forms of "Maps" and "Collated" information:

Principal Mapping Sources	Ordnance Survey maps, archaeological maps and papers
Supplementary Mapping Sources	Tithe maps, local authority mapping etc
Principal Collated Sources	Directories, local authority records (committees, minutes, studies etc.), photographs
Supplementary Collated Sources	Local studies accounts, papers and technical articles

Further elaboration on types and forms of information is given in Appendix C. Perhaps the most useful sources of reference for a general enquiry into the industrial history of an area are the selection of commercial directories held in County archives. There are usually several publishers involved, although one of the more superior series is the Kelly's Directory series. This series appeared every few years, from the later part of the last century, and holds information in two ways. Firstly, an account of each parish, village, town or similar is given, with the location, situation, residents and features of note. This section includes a "register" of residents, and their various occupations, and as such presents a potential route for information gathering. The second referencing system is by profession or industry, and so lists various companies or individuals by their occupation, sorted on a county, as opposed to each settlement, basis. Consequently, a search through this latter list looking for potentially contaminative industries may produce a result, while more detailed information may be sought in the settlement-by-settlement breakdown.

Archivists can search a number of keywords, often still on a card index system, although they will not be able to put specialist interpretation onto the results of such a search. Consequently, although a search using a number of keywords may be initiated for action by an archive, some technical personnel input is required to screen the search and follow up on "second level" information. In addition, an archive may charge for time taken in searching.

4.2.1 Resource requirements - area enquiry

This approach is much more difficult to quantify than resource requirements for a site-specific enquiry, in that the resource requirements may vary according to geographical area and density of potentially contaminative industries.

However, given the above restrictions, it could be expected that a brief screen through local archives and information sources may take around 5 man-days, with a further 5 man-days for following-up leads and secondary sources. This approximation takes no account of any project management activity or reporting of results.

4.3 Site Screening

It is proposed that the wide variety of sites and radioisotopes outlined in Section 2 is structured into a decision framework to allow the rapid classification of a potential subject site, which may have been identified using the methodology above. This will also allow the prioritisation of sites for more detailed assessment, according to the specific type of industry and radioisotope encountered or suspected, over a geographical area. This is a form which will be readily useable by any local regulator who wishes to prioritise sites within their area, in particular the Environment Agency, who may have to deal with a number of sites with limited resources. Two main qualifiers are proposed, both of which will attract an assessment classification:

- Probability of radiological contamination. This may be influenced by the historical background to the industry or process, the potential volumes and forms of contamination and the size of the industry;
- The radiological risk to future or current occupiers associated with suspected radioisotopes. "Radiological risk" is the degree of additional risk attached to anthropogenic radioactive sources, which takes the form of excess death risk per year. Where the following land uses attract a higher qualitative classification, this simply means that the particular isotopes associated with this use are thought to arise in more concentrated forms. The term "anthropogenic sources" includes uses of both natural and anthropogenic radioisotopes, and excludes background radiation due to natural radionuclides.

The probability of radiological contamination reflects the perceived probability that past industries on a site have caused radioactive materials or residues present in buildings and infrastructure to have been disposed of over the site or left in place. For example, a site formerly used as a luminised instrument facility may attract a high probability of radioactive contamination in view of the potential for use and disposal of many uncontrolled and discrete sources of radioactivity.

The radiological risk also addresses the problem of unknown sources with a qualitative assessment of the types of waste potentially disposed to the site. A site suspected of having, for example, quantities of disposed incinerator ash from the destruction of luminised instruments will attract a higher risk weighting than one suspected of having a small quantity of tin slag utilised in drainage or civil engineering applications. Only low toxicity radioisotopes, such as tritium and carbon-14, would attract a "low" classification in this risk assessment.

This approach is summarised in Table 4.1.

Table 4.1 Qualitative Approach to Ranking Radioactively Contaminated Sites

Industry Type	Probability of Radioactive Contamination	Radiological Risk	Reason, If Any, For "High" Ranking
MOD	High	High	Widespread use and on site disposal of radium in military instrumentation
Munitions manufacture	Depends on types of munitions	High	Nature of radioisotopes
Metals processing and refining	Medium-High	Medium – High	History, scale
Mining and extractive	Medium	Medium	Scale
The Phosphate industry	Medium - High	Medium	Large scale processing results in concentration of uranium and thorium series radioisotopes
Gasworks	Medium	Low-Medium	
Landfill sites	Dependent upon age of site and types of waste accepted	Medium-High	Historically used for disposal of some radioisotopes
Luminising Works	High	High	History of on site disposal of luminising materials
Gas Mantle manufacture	High	High	History of on site disposal
Non-ferrous metals	Medium	Medium	
Coal fired power stations	Medium	Medium	
Shipbreaking sites	Low-Medium	Low – Medium	
Chemical plants	Dependent upon catalysts used.	Low – Medium	
Incinerators	Dependent upon types of wastes accepted	Medium-High	
Scrapyards	Dependent upon types of wastes accepted	Medium	
Industrial processes and applications	Medium – usually inventory related	Low – Medium	
Laboratories	Dependent upon catalysts and reagents used	Medium	
Hospitals and clinics	Dependent upon age	High	History and "size" of sources used
Construction Industry	Dependent upon locally won material	Low – Medium	

4.4 Desk Study on Individual Sites

Following a proposal for re-use, redevelopment, or remediation of a site, it must be established whether there is any potential for contaminating activities to have taken place on that site. It is commonly accepted industry practice (CIRIA, 1995; BSI, 1988) that suitably experienced professionals should undertake detailed document reviews and site inspections, prior to any physical investigations. The aim of these should be to establish whether there is, in fact, any need to proceed with such investigations given the identification of any potential for contamination. There are a number of detailed studies on the sequence of site prioritisation actions, specifically DOE (1995), which specify the completion of a comprehensive desk-based review of information and status of the site as the first step in categorising a site. Dependent on the outcome of the preliminary investigations, further works could be proposed, possibly consisting of:

- Confirmation of suspected hazards or identification of any new hazards;
- Immediate actions to control any potentially acute hazard;
- Health and Safety considerations;
- Identification of requirements of further work, (e.g. more detailed desk studies may be required where a site is very large, complex or under different ownerships);

The following sections will consider the specific process by which a potentially radioactively contaminated site may be initially identified using a preliminary investigation, or Desk Study.

4.4.1 Sources of information

Information to identify and define a hazard may be acquired using a wide variety of methods. These are detailed in industry best practice literature from the Construction Industry Research and Information Association (CIRIA), British Standards Institute (BSI), the Institute of Civil Engineers (ICE) as well as from the former Department of the Environment (DOE), now a part of DETR. Coupled with extensive consultancy experience in this area, these methods and information sources are elaborated in detail in Appendix C.

Information should be sourced to give a complete picture of the condition of the site and its local environmental setting, including but not only historical operations, allowing an initial assessment of the environmental sensitivity of the site and surrounding area to be made. The more specific case of a potentially radioactively contaminated site presents complications in terms of the information inspected. It may not be possible, from direct sources, to identify a site that may be potentially contaminated with radioactive materials *inter alia*. Such a site may instead be interpretatively identified using knowledge of or information on processes or industries previously present on the site, and so any such study will only be indicative as opposed to conclusive. For example, a typical site review may result in the following information sourcing sequence:

i) Site identified on historical Ordnance Survey maps as "Works";

ii) Site identified on local town map as "ABC Instruments";

iii) "ABC Instruments" summary in local trades directory of similar date to local map;

iv) Trades directory listing the production of luminescent instruments as part of the activity on the site.

Alternatively:

i) Site identified on OS maps as "St George's Works (Engineering)";

ii) Library local history section contains details of St George's Works, detailing layout, activities and products, including a reference to gas mantles.

Many other indirect routes to a conclusion exist, such as part of the site being subject to previous authorisations, developed as part of a neighbouring works, now demolished, and so on. Local knowledge, in particular local history accounts, long-standing residents and previous employees, all represent possible means to collect qualitative information which may provide a lead to more concrete and quantitative information.

4.5 Qualitative Risk Assessment

The output of Desk Study information is usually in the form of a report, in order to present the information in a clear and concise manner. Generally, such a report will be constructed of a number of sections each representing a conceptual stage in the process.

Introduction

The front end of the report should summarise the site "management context" (i.e. current and intended strategy for the site), and include information on the background to the site; the full site address and the proposed end use, whether residential, commercial or industrial. A list of information sources and references is helpful, which could include the following, in addition to any outlined in Appendix C:

- Site Manager;
- Current occupiers or users of the site;
- Any Site Occupier suggested or required Consultee;
- British Geological Survey, geological map and borehole information;
- Ordnance Survey (OS) 1:50 000 and 1:25 000 scale topographical and other mapping;
- Local Aquifer Vulnerability mapping;
- Local Authority: some buried service information - street lighting, road drains, occasionally sewer records, Air Pollution Control authorisations, planning/building control department (information on the planning history of the site), archaeological Sites and Monuments Records holder;
- Local Environment Agency: Integrated Pollution Control authorisations, water resources, pollution control, Radioactive Substances Authorisations, development control information;
- Local utilities: buried electrical, gas, water, sewerage and telecommunications services information.

Site Description

This section summarises and condenses all the information sourced on the nature of the site. It includes general data on location and a general site description, both forms of National Grid reference, and the locality / local authority area. More specific information can include the site area in hectares, whether there are any access restrictions, site visit photographs, general layout and site boundaries, and a summary of areas of utilised and non-operational land. If operational, a full picture of the plant and activities taking place on the site is needed and, if occupied, information on number of occupants, residence times and other factors needs to be gained. There should be a summary of boundary construction materials, heights and lengths, and whether there is a gradient across the boundary, such as terracing, and whether this may prejudice neighbouring areas. Details of immediate site surroundings, and a summary of immediately adjacent land uses, as well as the more general setting with details of proximal land uses, give the physical setting of the site with respect to potential off-site sources and receptors of contamination. To aid any assessment of risk, information on the effectiveness of the boundary in acting as a barrier to the migration of surface runoff, airborne dust, subsurface lateral flow, unauthorised access, or whether the boundary divides the modern site from any former areas of the site should also be included. The neighbouring land uses may have varying human sensitivity; for example, residential, school and recreational uses have a higher sensitivity than office or industrial uses, which in turn have a higher sensitivity than railways, derelict land or woodland.

As well as detailing the obvious structures on the site, details of any above-ground or buried tanks, any bunding or barrier wall around such tanks, type of tank (liquor, suspension or interceptor tank), and potential contents are of interest when focussing an intrusive site investigation. Underground or aboveground services information can be summarised by utility or by service type, and where the service crosses the site boundary.

The types and proportions of ground cover over the site will reflect the susceptibility of any potential contaminants to mobilisation and transport through weathering processes, and the degree of radioactive attenuation likely to be available to near-surface contamination. Permeable, partly permeable and impermeable areas of the site can include:

- buildings and structures;
- hardstanding;
- exposed soil;
- vegetation and scrub;
- gravel or loose fill.

The overall nature of the ground cover material is also of interest, in terms of the respective numeric proportions of permeable and impermeable cover and any evidence of recent flooding or ponding of water over the site. In addition, the Hydrometric Register should be referenced for the approximate annual rainfall (mm/a) in the area. Details of any obvious site drainage infrastructure and visible discharge points, as well as a description of any sloping ground on the site, whether it is constructed (e.g. terraced or embankment) or natural, and the direction in which the slope is falling in elevation, will also provide valuable information input.

Site visits form a very important part of the study, and much information can be gained using visual and basic instrumentation clues. Observations of surface contamination (including details of area affected, estimated thickness (m), any temporary remedial measures taken, such as fencing or covering) are of interest. Is any surface contamination deposit or exposure easily accessible by people on the site? Can it be mobilised as airborne dust? This section can also include details of general fly tipping and ad-hoc waste disposal, as these may pose additional risks to site visitors, users or occupiers. Basic radiological instrumentation could be used during the site visit to check any surface deposits or exposures of contamination, particularly when quantities of ash, with potentially quite elevated levels of contamination, are encountered. The instrument could also be used to check any drains or outfalls, as well as typically contaminated areas in buildings, such as beneath windows, around sinks and at the edge of work surfaces.

Environmental Setting

This section considers, in particular, the geological, hydrogeological and hydrological setting of the site.

Data sources for geological information include the BGS "One-inch" series of Solid and Drift geological maps and BGS sheet memoirs, BGS registered boreholes in the vicinity of the site, borehole or trial pit records from previous site investigations or commercial site data reports. Questions which should be addressed to allow geological characterisation of the site include:

- Is Made Ground suspected or known to be on the site from previous SI reports; if so, what is its thickness; is it continuous or sporadic?
- Are there any drift deposits overlying the bedrock beneath the site; if so, what do they consist of; are they continuous; what is their suspected or known thickness?
- What is the bedrock geology of the site - if it includes Coal Measures, is there a history of coal mining in the area?

Hydrogeological classification of the site can allow prioritisation of any remedial measures. Potential issues include:

- What is the Environment Agency aquifer classification for the underlying groundwater? Similarly, what is the vulnerability classification? This data may be gained from the Groundwater Vulnerability mapping (1:1 000 000 or 1:100 000 scale) or direct consultation with the EA.
- Is the underlying aquifer known to be contaminated; if so, is the site or an immediate neighbour the source of contamination?
- What are the shallow groundwater flow regimes?
- Is there a lateral flow onto the site (from a watercourse or channel), and is there a perched water table beneath the site?
- Is there a Source Protection Zone (SPZ) modelled around the site? (data available by direct consultation with EA);
- Are there any licensed abstraction boreholes within 2 km of the site?
- If the site is located near the coast, is any tidal effect on the groundwater anticipated?

The hydrology of the site should be addressed in terms of any surface water features within 1 km of the site and their type (river, stream, lake, sea); the distance between the site and the feature and intervening ground, any data on General Quality Assessment (good, fair, poor etc)? What is the approximate flow rate? Are there any water abstractions within 500 m of the site? What are their end-uses?

Are there any landfill sites, waste disposal or other licensed waste operations within 2 km of the site? Data for this section may be sourced from historical maps, Local Authority, Landmark Envirocheck, Aspinwall Sitefile Digest, BGS Registered landfill sites etc.

Are there any sensitive ecological targets within 1 km of the site? These may include SSSI, National Nature Reserve, Marine Nature Reserve, Conservation Area, Special Protection Area, livestock, crops and game animals. Responses to the DETR (1998) Consultation Paper on radioactively contaminated land contained several differing definitions of "receptor", one of which was wildlife and environment. However, the ICRP approach is that the protection of humans will ensure the protection of all organisms.

Site History
The site history appraisal should address what is suspected to have occurred at the site, with referenced sources, such as the following:

i) Historical Ordnance Survey (OS) Maps - for example; published in 1864, 1903, 1924 (Scale 1:2500);

ii) Local Study libraries and Local Authority Planning sources;

iii) Other sources from Appendix C.

The summary should include details of former site uses, former neighbouring land uses, plant and buildings present on the site at various stages in development and the date of cessation of activity. It should also address any potentially on-site contaminative former uses of the site (such as: chemical works, tannery, fuel storage, scrapyard, steelworks, landfill, metal or oil refining, coal mining, sewage works, railway, or any other potentially contaminating activity), which could have resulted in a wider contamination profile. In addition, any potential neighbouring contaminative former land uses may have had a peripheral or migratory influence on the site contamination profile. Infrastructure from the former use may still be in use, introducing potentially complex exposure pathways for workers engaged within it, while redevelopment of a site for a change of use may have only removed structures to ground level.

Although it may constitute a reiteration of information, include details of any former above ground or buried tanks, any bunding or barrier wall around such tanks and the type of tank, with reference to the information source and potential reliability.

Often it is helpful to enquire with the local Sites and Monuments Record (held by the Local Council or County Council), which may reveal whether there are any potential cultural heritage interest issues associated with the site or the surrounding area, including archaeological sites or listed buildings. The results of this enquiry may have an effect on the remediation or redevelopment of the site.

Have any site investigations previously been carried out upon the site? These could take the form of owner or regulator boundary surveys or previous intrusive site investigations, for geotechnical or environmental assessment. What were their general findings?

4.5.1 Interpretation and Risk Assessment

General Approach
With reference to the information gathered in the first part of the exercise, a risk assessment may be carried out to determine the status of risk posed by the site. The aims of this assessment should be along the same lines as those for the conceptual "hazard assessment" stage (EA/DETR, in preparation); to obtain sufficient information on the site, including existing or proposed use and environmental setting, to develop a conceptual model for the site and gain a preliminary understanding of its risk profile. The risk assessment can be based on

the established **Source – Pathway - Receptor** methodology outlined in Section 1.3. The pollutant linkage, in order that a risk is present, will require all three of the terms to be present.

The **Source – Pathway - Receptor** relationship allows an assessment of potential environmental risk to be determined, based on the nature of the source or hazard, the degree of exposure of a receptor to a hazard and the sensitivity of the receptor. Should one of the three terms be absent from the assessment, for example, a source and pathway but no receptor, then the assessment may reflect this in terms of a low liability, although the hazard remains.

On this basis an assessment is then made of whether there is potential for the threshold values for dose and risk to be exceeded. The assessment may also include any estimates or measurements of dose arising from the potential for radioisotopes to be present on the site, allowing ranking and prioritisation of risks.

In DETR (1998), the authorisation of radioactive wastes by regulators is achieved through the source – pathway – receptor approach outlined above, with an assessment of radiation doses resulting from the exposure to the "critical group", or the most exposed group of people. Consequently, the whole population is protected if adequate protection is given to this group.

4.5.2 Report recommendations

The Phase One report should identify the probability and possible severity of any likely radioactive contamination. The likely contaminating isotopes, concentrations and distribution of radioactive material should be identified and this information can then be used in order to scope any proposed site investigation.

4.5.3 Resource requirements - site specific Desk Study

The primary activity of a desk study is to collate as much information about the past uses and present status of a site as possible, and interpret this in a form compatible with the hazard identification process. The resource requirements for a desk study, and the various project aspects, can be summarised as shown in Table 4.2.

Table 4.2 Resource Requirements for a Typical Desk Study, for a Site Suspected to be Contaminated

Activity		Time Budget – Days
i)	Project Management	2 man-days
ii)	Data Collation: site walkover, site records review, local library visit, regulator and Local Authority document source acquisition, review of other records	5 man-days
iii)	Data Interpretation	3 man-days
iv)	Report Preparation	5 man-days
v)	Report and Project Review	2 man-days

However, given that some sites may involve a greater or lesser amount of work, these resources may alter. Project complexity, and thus time involved, can depend on a wide range of factors, some of which are outlined below:

- Size and location of site;
- Range of past historical uses;
- Extent of the built environment on the site, including plant, buildings and services;
- Information availability;
- Proximal land uses;
- Range of issues upon the site;
- Health and Safety implications, security implications;
- Existing data on the site status.

4.6 Further Risk Assessment

Sections 4.2 to 4.5 have detailed the commonly followed stages for a desk study, which is comparable to the initial phase of risk assessment, Phase 1a, as laid out in the Model Procedures for managing contaminated land. Further risk assessment work, including intrusive investigations and quantitative survey work, would constitute hazard assessment work under the Phase 1b stage. This would then lead on to evaluation and selection of remedial measures and, finally, the implementation of risk management actions. The work involved in Phases 1b and 2, specifically addressed at radioactively contaminated land, is detailed in Section 6.8, as the initial site survey and initial categorisation.

5. A REVIEW OF AVAILABLE CHARACTERISATION TECHNIQUES

There is a wide range of characterisation techniques available for the assessment of levels of radioactivity in contaminated land. The choice of technique is dictated by the contaminant, the presence of interfering background radiation and the desired minimum detectable activity of the contaminant. For some situations direct monitoring is feasible, for example when dealing with a penetrating gamma emitter and seeking to identify areas where activity levels are generally in excess of 1 Bq g^{-1}. In this situation a simple large volume sodium iodide scintillation detector connected to a ratemeter will be adequate. In other circumstances, when dealing with low energy pure beta emitters, sampling followed by radiochemistry and counting is often required. This vastly increases the time and the cost required per data point.

5.1 Direct Monitoring for Gamma Emitters Using Hand Held or Portable Equipment with Limited Spectrometric Capability

Historically site remediation exercises have often been based on a comparison of the gamma dose rate one metre above ground level with a reference value obtained somewhere else on, or nearby, the site. The reference area was selected on the basis that it was uncontaminated and was expected to have the same background radiation level as the area being remediated. There is considerable logic to this method when the impact of any contamination on site occupiers is mainly external gamma radiation. A maximum annual effective dose can be converted to a maximum acceptable air kerma rate by taking into account occupancy and shielding and using a conversion factor of 0.86 Sv (effective dose)/Gy (air kerma). This technique is discussed fully in HMIP (1995). Typical background gamma air kerma rates fall in the range 0.02 to 0.15 μGy h^{-1} (2).

Most recent exercises of this type have employed the Mini Instruments 6-80 monitor. This instrument was designed specifically for the measurement of low air kerma rates. Many local authorities employ this instrument as part of their emergency response to nuclear accidents. Some authorities have more extensive monitoring programmes within which the instrument is employed to investigate the consequences of discharges from nuclear and other sites. It employs a large energy compensated Geiger Muller detector, which has a basic sensitivity of $16s^{-1}$ μGy h^{-1} and a response which is reasonably independent of gamma ray energy for energies from 60 keV upwards. It also responds to cosmic radiation, which typically generates approximately $1s^{-1}$, and it also has a low inherent background, caused by ^{40}K within the glass components of the detector, which generates 0.2 s^{-1}. Typical environmental gamma air kerma rates generate between $0.3s^{-1}$, at 0.02 μGy h^{-1}, and $2s^{-1}$, at 0.13 μGy h^{-1}. The detector is connected to a scaler timer, which can be set for a range of counting times from 10 s upwards.

Normally a counting time of 600s is employed which generates an integrated count of between 900 and 1500 counts in most circumstances. For areas of uniform geology it will be possible to identify areas of the site which produce an excess count rate of the order of 200 in 600 seconds, or $0.3s^{-1}$. This corresponds to an excess air kerma rate of approximately 0.02 μGy h^{-1}. Occupancy for 2000 hours with no shielding would produce an annual effective dose of approximately 35 μSv.

If the site is complicated, with, for example, areas of low background from soil and areas of much higher background produced by the use of granite chippings or by relatively active brick work in surrounding buildings then typically an excess of 1000 counts in 600 seconds may be required to identify an area as contaminated. This corresponds to 1.7 s^{-1} or approximately 0.1μGy h^{-1}. For 2000 hours occupancy and no shielding, this gives an annual effective dose of 170 μSv.

Measurement at a height of 1 metre with an uncollimated detector produces results with a poor spatial resolution, because the air kerma rate at that height, for uniformly active ground, is mainly generated by radiation incident on the detector at between 45° and 80° to the vertical (Beck *et al*, 1968). Hence relatively small areas of enhanced activity will not show up well.

Monitoring is normally carried out at pitches of 2 to 10 metres, depending on site conditions. Using a 5 m pitch, i.e. monitoring every 5 m along a series of parallel lines 5 m apart, gives 400 readings per hectare. At 600 seconds per reading and allowing 120 seconds for movement this gives a monitoring effort of 80 hours per hectare. This is relatively slow in comparison with other methods. If a higher minimum detectable air kerma rate is sufficient then the counting time can be reduced, to 300 or 100 seconds, giving a commensurate reduction in time per hectare. Additionally three detectors can be connected in parallel to one ratemeter, allowing a reduction in counting time to 300s with an improved precision.

The same end point can often be achieved more quickly using relatively large volume sodium iodide or caesium iodide scintillation detectors. These have the advantage of a much higher count rate, typically 50 to 200 s^{-1} for a 51 mm x 51 mm detector at normal levels, which means that shorter counting times can be employed for a particular statistical precision. Their disadvantage is that they have a large change in response with radiation energy. For example the response of a 51 mm x 51 mm sodium iodide detector has a low energy maximum of 6000 s^{-1}μGy^{-1}h at 60 keV, a response of 1500 s^{-1}μGy^{-1}h at 662 keV (^{137}Cs γ radiation), falling to 1000 s^{-1} μGy^{-1}h for γ radiation from radium-226 in equilibrium with its daughters. If the impact on site occupiers is mainly external gamma radiation then this variation in response with energy introduces an uncertainty. It is often possible to reduce this uncertainty by a process of inter-comparison between the sodium iodide detector and a Mini Instruments 6-80 monitor or other similar instrument of good dosimetric properties, provided the contamination fingerprint is relatively constant across the site. Depth of burial will have some influence on the ratio of the instrument readings. Activity deposited on or within a few mm of the surface will produce a radiation spectrum at one metre which is similar to the theoretical decay spectrum. Buried activity will produce a spectrum which is a combination of the decay spectrum and Compton scattered, lower energy, photons. These photons have a lower dosimetric weight than higher energies, in terms of the number of photons incident on each cm^2 of the body per μSv (Table A21 (ICRP, 1996)) but a higher detection probability for the sodium iodide detector. Hence the ratio of the net count rate from the sodium iodide detector to the excess air kerma rate will increase as activity is buried, up to the point at which attenuation is sufficient to screen activity effectively, which is typically 250 mm for a 10 mm thick layer of activity 30 times that of the natural activity.

In dosimetric terms, the response of a typical 51 mm x 51 mm sodium iodide scintillation detector is approximately 1000 s^{-1} μGy^{-1}h for radium-226 γ radiation. Typical background count rates range from 30 s^{-1} to 100 s^{-1} for low background materials, up to 200 s^{-1} when used in an alleyway between brick walls and up to 400 s^{-1} when used close to granite walls.

Typically, some knowledge of the expected background count rate will allow the detection of excess count rates in the range 30 to 100 s^{-1} using a typical ratemeter, one with a response (or averaging) time of one or two seconds. This corresponds to an excess air kerma rate of 0.03 to 0.1 μGyh^{-1} and an annual effective dose for 2000 hours exposure and no shielding of 50 to 160 μSv. Again the same averaging over an area takes place but site practice typically involves walking lines two to five metres apart observing the ratemeter, listening to the audio output and noting any area where the count rate appears unusually high. Typical walking pace in these circumstances is 1 m s^{-1}, giving an hourly coverage of 0.7 to 1.8 hectares.

Larger detectors, such as the 75 mm x 75 mm detector often used with the AEAT Groundhog System, are commensurately more sensitive to contamination but also have a higher background count rate. The improvement, in terms of the minimum detectable excess air kerma rate, is approximately the ratio of the diameters, giving a minimum detectable increase of between 0.02 μGy h^{-1} and 0.06 μGy h^{-1} for an individual reading. The Groundhog System and similar systems, have an efficient data storage capability which typically stores counts below an energy window, counts within an energy window, and counts above a window together with an accurate measurement position, often within ± 0.5 m. The resulting data can be displayed on a VDU, or printed out, and correlated with ground features, such as walls and roads. Using a colour presentation easily shows up areas where the general count rate is only slightly in excess of the surrounding background areas allowing the identification of areas with enhanced levels only a few percent above background. This capacity is enhanced where the contaminant is not present in natural background radiation. The counting window can be set up to detect the photo peak generated by the gamma radiation from the contaminant while the signal above the window can be used to predict an expected background count rate within the window. This can be subtracted from the count rate within the window to yield a better measure of the net count rate from the contaminant, typically allowing a minimum detectable level of less than 0.02 μSv h^{-1}, even for areas of variable background.

In some situations thinner detectors can be employed with advantage. This is where the contaminant is a low energy gamma emitter such as ^{241}Am (60 keV). A photon of this energy is likely to be completely attenuated by a layer of sodium iodide 3 mm thick. Using a thin crystal has the advantage that the background count rate is greatly reduced. As an example, a typical 125 mm diameter, 3 mm thick crystal has a background count rate of approximately $100s^{-1}$ without any pulse height analysis.

The comparative value for a 50 mm thick crystal is approximately $500s^{-1}$ in similar circumstances. With the addition of a simple counting window the background count rate with the thin detector can easily be reduced to $20s^{-1}$ without influencing the response to 60keV γ radiation at all.

The analyses above have concentrated on the measurement of air kerma rate where external gamma radiation is the major contributor to effective dose for the site occupier. The same equipment can also be used to predict soil activity levels in Bq g^{-1} for γ emitting nuclides where inhalation and ingestion are the important pathways. Use of uncollimated equipment invariably implies an effective but ill defined averaging volume. The higher the equipment is held off the surface, the larger the effective averaging area and the smaller the impact of a point source directly beneath the detector. Gamma radiation from nuclides such as the radium daughters lead-214 and bismuth-214 is also penetrating, with attenuation coefficients of approximately 0.1 cm^{-1}. Activity down to at least 250 mm contributes significantly to the surface radiation field. For a detector held in contact with the surface, activity out to 2 m contributes to the signal although for a unit volume the closer the activity is to the surface and the closer to the detector the higher the contribution. As an example a point source 0.1 m from the detector on the surface contributes 400 times the signal of a similar source on the surface at 2 m from the detector and 80 times the signal of the same source buried at a depth of 0.25 m below the detector. For a detector 1 m from the ground the corresponding volumes are 5 and 20 times.

It is possible to convert the count rate from such a detector to an average activity level (in Bq g^{-1}) relatively easily, provided one remembers that the end value is an average over a relatively ill defined area and depth. The process relies on the simplification that for an infinite volume a gamma photon can be assumed to deposit its energy within the volume, i.e. none escape. The gamma dose rate within the volume is thus the photon energy generation rate per unit mass. Hence:

$D = A \times \Sigma E \times 1.6 \times 10^{-13} \times 10^{6} \times 3600$

Where D is the dose rate (μGy h^{-1})

A = activity concentration (Bq kg^{-1})
ΣE = total energy emitted per decay (including daughters present)(MeV)
1.6×10^{-13} converts MeV to Joules
10^{6} converts Gy (J kg^{-1}) to μGy
3600 converts Bq to disintegrations per hour

Thus $D = A \times \Sigma E \times 5.8 \times 10^{-4}$

For a semi infinite volume, i.e. at the surface of a large area of contaminated soil the dose rate is approximately half the above value. Hence

$D = A \times \Sigma E \times 2.9 \times 10^{-4}$

For lower energy radiations there should be a correction for the difference between the mass energy absorption coefficients for soil and air but this is not significant for most situations and will be ignored.

For ^{226}Ra, when the decay chain is in equilibrium, the total decay energy per head of chain decay is approximately 2.5 MeV. Hence, for 1 Bq g^{-1} or 1000 Bq kg^{-1}

$D = 1000 \times 2.5 \times 2.9 \times 10^{-4}$

$= 0.725$ μGy h^{-1}

Comparison with the values previously derived for the Mini 6-80 or the 51 mm x 51 mm sodium iodide detector shows that this value is of the order of 30 times the minimum detectable activity. It is thus possible to identify contamination at levels of the order of 0.03 Bq g^{-1} for energetic γ emitters, such as radium-226 and cobalt-60, falling proportionally with total γ emission per head of chain disintegration, to, for example, 0.15 Bq g^{-1} for a total of 500 keV.

Again any energy analysis of the signal will improve the minimum detectable activity. For contamination by caesium for example, counting between 0.2 and 0.7 MeV will reduce the background count rate by approximately a factor of three for a typical large sodium iodide detector, while not reducing the signal, in comparison with a counter with a lower energy threshold only of 60 keV. This reduction in background count rate will reduce the minimum detectable activity by a factor of 1.7.

The sensitivity of the technique is such that it can sometimes be used where a considerable proportion of the activity present does not emit γ radiation, provided the ratio of energetic γ emitters to total activity remains fairly stable. A classic example is a mixture of caesium-137 (γ emitter) and strontium-90 and yittrium-90 (beta emitters). Calculation of the annual effective dose per unit activity can be used to generate a maximum acceptable γ emitter concentration. Control of that concentration will thus lead to acceptable occupier doses. Because the ratio of γ to total activity is normally variable, control should be established for the minimum likely ratio, which will lead to a conservative result. The advantage of this process is the much reduced monitoring cost. An in-situ gamma measurement typically costs 5% of a radio chemistry based strontium-90 measurement, and provides instant answers. It can thus be used during any remediation exercise to identify, almost instantly, when sufficient soil has been removed to achieve the desired maximum acceptable activity. It can also be used for the final sentencing for disposal of removed soil etc.

5.2 Direct Monitoring Using Equipment with Significant Spectrometric Capability

Three types of equipment fall into this class. They are:

i) hand held sodium or caesium iodide scintillation based units

ii) vehicle mounted sodium or caesium iodide scintillation based units

iii) vehicle mounted units employing intrinsic germanium semiconductor detectors.

5.2.1 Hand Held Sodium Iodide or Caesium Iodide Scintillation Based Units

With the advance of microelectronics it is possible to produce hand held sodium or caesium iodide scintillator based units which have true spectrometric ability. Typically the output from the detector is fed into a 256 or 512 channel multi-channel analyser. The instrument is set to count for an appropriate period and the result displayed on a liquid crystal display and stored in a memory. The unit normally can also be asked to search for the presence of particular nuclides stored in its library and to employ a user defined calibration factor to generate values of Bq g^{-1} of that nuclide, again based on the assumption of a large volume source. Such units are often derived from geophysical exploration equipment and are significantly more robust than normal analysis equipment. The advantage to the user comes mainly from the ability to handle areas where there is no stable fingerprint, i.e. the ratios of the various γ emitters present vary significantly over the site. The minimum detectable activities are also enhanced for nuclides where the photopeak does not correspond to photopeaks produced by the normal components of background radiation, i.e. the uranium-238, thorium-232 and uranium-235 decay chains and potassium-40. The spectrometric ability of the equipment is limited, however, by its relatively poor energy resolution, typically 5 to 10% for 662 keV γ radiation. This implies that the displayed photopeak energy spectrum for caesium covers the range 600 keV to 720 keV. One of the decay lines of bismuth-214 has an energy of 609 keV, which overlaps with the caesium-137 signal, increasing the background and the minimum detectable activity.

5.2.2 In Situ Monitoring Using Semiconductor Spectrometers

In areas where the mix of radionuclides present is variable, and where these nuclides contribute differently to dose per unit activity, then the additional spectrometric capability of semiconductor spectrometers can be useful. They differ from scintillation detectors in various ways. The most important difference is their very high energy resolution, which allows differentiation between very close γ energies. They are inferior to sodium iodide detectors in some ways. It is not possible to produce single detectors of very great size as this limits the detection efficiency. The atomic number of germanium, the commonest material, is lower than that of sodium iodide which both reduces the detection probability and reduces photo fraction. However it is possible to purchase detectors which have 1.5 times the photopeak efficiency of 76 mm x 76 mm sodium iodide crystals. These will have more than sufficient sensitivity for the vast majority of measurements associated with remediation exercises. The other problem is that they require cooling to low temperatures, either electrically or, normally, with liquid nitrogen. The cooling system inevitably adds weight and bulk.

Detectors of this nature are sometimes employed using a collimator, which defines their field of view although reducing their portability. The unit is put in place, and a count started. After a few minutes, typically, a detailed spectrum of the gamma radiation striking the detector will have been obtained. This spectrum can then be analysed rapidly to identify the nuclides present. This process is simplified if the likely contaminants have already been identified. The number of counts in each photopeak can then be converted to the number of photons of that energy striking the detector. This value can then be converted to the activity in Bq g^{-1} for that nuclide for the area inspected by using the normal simplifying assumptions that the activity in the soil is uniform with depth and extends to a depth of at least 200 mm. This conversion factor can be derived mathematically using programmes such as MCNP or Microshield and is sometimes confirmed experimentally using point sources buried at a range of depths in sand to mimic the effect of activity distributed within the soil.

Typical lower limits of detection for such measurements are normally less than 0.1 Bq g^{-1} for nuclides with a high probability of the emission of energetic gamma radiation.

To summarise, the use of intrinsic germanium detectors is normally only justified where the contaminant is a complicated and variable mixture of gamma emitting nuclides.

5.2.3 Gamma Monitoring by Vehicle Mounted Units

Vehicle mounted units have considerable advantage when dealing with large open areas. The equipment weight used for walkover surveys is limited to a few kg for handheld units and perhaps 20 kg for backpack units. This almost automatically precludes the use of collimators to define the monitoring area. It also precludes the use of really large detectors, not only because of weight but also because of the high probability of damage. Contrast this with vehicle mounted equipment, where it is possible to deploy several detectors at once, allowing detailed measurements over an area of a few metres wide in one pass. The vehicle can carry more sophisticated electronics, allowing real time spectrometry and data analysis, and can also either provide a power supply from its engine alternator or from large batteries. It is also easier to weatherproof equipment carried on a vehicle.

Larger scintillation detectors offer improved lower limits of detection for a defined monitoring period. The improvement over a smaller detector is approximately the square root of the ratio of the areas for detectors which are at least 50 mm thick. In many remediation situations this improvement in minimum detectable activity is likely to be irrelevant. The main advantage of the increase in size is to allow an increase in the monitoring speed from the 0.5 to 1 m s^{-1} employed for handheld units up to a few m s^{-1}. Vehicle mounted units are thus very attractive for site clearance exercises on airfields and other similar open sites. Use on a redeveloped site is likely to be less attractive because of the problem of manoeuvring around buildings and other obstructions. There has also been a history of problems with engine propelled vehicles which have tended to struggle when forced to operate for long periods at low speeds. Electrically propelled vehicles are much more tractable in such situations.

A notable instrument in this category is the BNFL LARCH (Large Area Radioactive Characterisation) system. This uses a high resolution gamma ray spectrometer, based on an intrinsic germanium detector, combined with a Global Positioning Satellite (GPS) system to locate and identify activity. The detector is collimated to view a 2 m x 2 m square. At a speed of 0.1 m s^{-1} the minimum detectable caesium-137 activity is approximately 0.01 Bq g^{-1}. Correspondingly, at 1 m s^{-1} the minimum detectable activity will be approximately 0.1 Bq g^{-1}. Values for nuclides which are present naturally but may be present in enhanced levels will be higher than this. However provided it is possible to find a suitable background area they will not exceed 1 Bq g^{-1} head of chain activity for the uranium-238, thorium-232 and uranium-235 decay chains, at a coverage of 4 m^2s^{-1}, or 1.4 hectares per hour.

5.3 Other In Situ Measurements

5.3.1 Gross Beta Measurements

Normally it is unusual to perform anything other than gamma measurements in situ. It is normally easier to remove samples for situations where gross alpha and gross beta measurements are useful. Even very limited amounts of treatment, such as the removal of roots, twigs and other debris, reduces the likelihood of damage to the detector and also improves the meteorological quality of the measurement.

In some circumstances, however, it is possible to perform gross beta measurements in situ using large area beta detectors held close to the soil surface in trial pits. The technique is particularly useful for uranium-238 detection. This nuclide decays by alpha emission to thorium-234 which then decays with a half life of 24 days to protactinium-234. This nuclide has a half life of 78s and decays mainly via an energetic beta emission with a E max of 2.31 MeV. This is reasonably penetrating, with a range up to approximately 10 mm in soil. Hence an air gap between soil and detector window of a few mm or tens of mm's is not particularly important. It may well be advantageous to have a significant gap, not only because it reduces the risk of damage to a thin windowed detector but also because it will effectively screen out the small alpha component which will be present The instrument employed should have a large area detector (100 cm^2 upwards) connected to a scaler timer unit. It can be calibrated using the method suggested in Section 7.2, EUR, (1998). As an example, the Berthold LB1210C, which has a large area thin windowed gas refillable proportional counter, has a response of the following form:

$$R = 2.8\,(E - 0.1)^{1.25}$$

Where R is the response, s^{-1} Bq^{-1} g and

E is the maximum energy in MeV.

For protactinium-234, this yields a response of 7 s^{-1} Bq^{-1} g above a typical background of 5 to 10 s^{-1}. This excess level is normally identifiable using the ratemeter only. Employing the scaler timer function can reduce the minimum detectable level considerably, with an improvement by a factor of 4 for a 60 second count. It is thus possible to identify contamination by uranium-238 in soil in situ for levels of approximately 0.25 Bq g^{-1} upwards using this technique.

5.3.2 Radon Monitoring

In some circumstances deliberately buried radium could give rise to relatively high radon levels in buildings. Monitoring of radon is an established process which can employ either active sampling, where air is drawn through a filter paper and then the filter paper is removed and counted, or passive sampling, where the radon diffuses into a scintillation counting cell or is adsorbed onto activated charcoal which is then subjected to gamma spectrometry. The most popular method in Britain, however, uses CR39 plastic within a holder. The radon diffuses into the holder and decays. A proportion of the decay products settle onto the CR39 and then decay further. The CR39 is thus bombarded generally with alpha particles, which damage the plastic. The damage tracks can be etched out using sodium hydroxide to produce readily visible and countable pits in the plastic which can be counted automatically. The density of tracks can then be converted into an effective dose rate, provided the exposure period is known. The process is relatively economical, a few pound per measurement. The only problems are that of taking account of seasonal fluctuations in average radon levels in buildings and also of changes in building occupation level changing the ventilation further.

5.4 Measurements Employing Sampling Techniques

Sampling techniques have to be employed when the radionuclides which may be present as pollutants cannot be monitored directly i.e. they do not produce a significant fraction of energetic gamma photons or beta particles per decay. Sampling techniques may also have to be employed where there is a reasonable probability of levels of activity being brought to the surface by garden cultivation, for example, which could give rise to unacceptable doses, or for other similar circumstances where knowledge of the activity with depth is required.

For remediation surveys normally measurements at or close to the surface will be required. Soil samples can be obtained using trowels, for the first 100 mm of soil, bulb planters for depths up to 150 mm, and a variety of tubular samplers which are forced into the ground for depths up to 1 metre. The core contained within the tubular sampler can be removed, in some designs by splitting the sampler along its length and in other designs by pushing the core out. The former is preferable because it reduces the smearing effect of the tube walls, which can distort the activity versus depth profile. In any case, where at all feasible, the outer surface of any core should be cleaned off to reveal the undisturbed centre, which can then be analysed.

The statistical basis of sampling is relatively complicated and is treated in Section 5.8. The initial decision is the area to be considered as one unit over which activity levels, for example, can be averaged. Examples could be one house plot or an entire sports field. Sufficient samples should then be taken to allow a good measure of the average over that area and also to allow the identification of unacceptably high levels of contamination over a significant proportion of the area under study. The same problems arise, to some extent, with walkover surveys but in that case the much lower cost per measurement point reduces the need to economise.

5.4.1 Gamma Spectrometry of Samples

Broadly the same measurements are performed on samples as during walkover surveys. The gross gamma activity can be assessed, or low resolution (scintillation) or high resolution (intrinsic germanium detector) spectrometry performed. The advantages of sample counting are:

i) the volume and mass is defined

ii) background reduction using shielding can be employed

iii) limitations on power and the use of liquid nitrogen are much reduced.

The end result is a generally much lower minimum detectable activity. The disadvantage is that it is a discreet, and often quite small, sample that is being processed. For sites where the activity is distributed as objects, rather than relatively uniform contamination, then the sampling often reduces to an assessment of the probability of collecting one of the active objects. For remediation, the reduction in minimum detectable activity is also normally not likely to be particularly useful as direct monitoring can normally identify areas with unacceptably high levels. Typical minimum detectable activities for a 50 mm x 50 mm sodium iodide detector, a counting time of 10 minutes and a sample mass of 200g are less than 0.4 Bq g^{-1}.

5.4.2 Gross Alpha Counting

This technique has been used for many years but has some serious disadvantages. The first stage of preparation involves sieving, to remove large particles, roots, twigs and debris, following by drying. The sample can then be formed to give a flat surface of effectively infinite thickness, i.e. at least 1 mm thick, or it can be placed in a ball mill and reduced to a fine powder which is then used to make a very thin layer source. Normally both samples are counted using a thin windowed proportional counter, which has a background of no more than a few counts per minute to yield a good measurement of the alpha surface emission rate. The main problem is the conversion of that surface emission rate into an activity. If the pollutant is present in the form of a relatively small number of relatively large particles then these will have a much lower surface emission rate per Bq than the corresponding mass distributed as a thin coating over a large number of soil particles. It may be possible to assess the physical form of the activity by performing radiochemistry on a representative number of samples which have been gross alpha counted and then deriving a calibration factor, if the ratio between the gross alpha count rate and measured total activity is reasonably constant. It is also possible to use CR39 plastic to perform auto radiography on samples. Discreet sources will show up as very high levels of local damage surrounded by relatively clear areas whereas well distributed activity will show up as a generally uniform fog of damage pits.

As part of the process of conversion of a measured emission rate into activity, spiking of samples by sand labelled with a known amount of alpha activity is sometimes used. Again differences in the effective thickness between pollutant and spike source can produce large uncertainties.

Another calibration route which can be employed but which also suffers from the problem of the effective thickness of the real source uses absorbers to build up an effectively infinitely thick plane source of the nuclide, or nuclide of similar energy, in question. This is addressed in paragraph 7.2 of EUR (1998). The resultant sensitivity for a large area, thin windowed, detector, the Berthold LB1210C was 0.3 s^{-1} Bq^{-1} g for protactinium-234 above a typical background of 0.02 s^{-1}. It is thus possible to measure apparent activity levels, ignoring the major problem of the effective thickness of the real source, to a level of 1 Bq g^{-1} for counting times of 100 seconds.

As in all measurements, the other major problem is the problem of background. Soils and building materials contain alpha emitters at levels between 0.03 and 1 Bq g^{-1}. On a large or complicated site the background level may change significantly, further reducing the quality of the results.

As a result of these problems gross alpha measurements are thought of as intrinsically unreliable by many. However, with care, the method can be used to identify areas which are significantly contaminated.

5.4.3 Thick Layer Alpha Spectrometry

As an improvement over the gross alpha technique, semiconductor alpha detectors can be used to perform spectrometry on thick samples, rather than the more familiar electroplated sources. This process relies on the fact that alpha particles emitted close to the surface of the source may deposit virtually their full energy in the detector. The pulse height analysis display looks like a series of saw teeth. The peak of the saw tooth represents a full energy deposition event while the relatively slowly declining area at slightly lower energies is composed of measurements of deeper buried alpha particles of the same nuclide and even deeper buried alpha particles generated by higher energy decay events. Inspection of the spectrum will reveal the nuclides present, derived from the full energy peaks, and some measure of their relative concentrations. The technique is particularly useful where the nuclide of interest is not present naturally in the samples and particularly where the level of natural alpha emitters varies across the site.

5.4.4 Measurement of Gross Beta Levels After Sampling

This has been considered in the in situ measurement section.

5.4.5 Radiochemical Analysis (alpha emitters)

Measurement of alpha emitting nuclides which have no convenient relatively short half life daughters that emit γ or energetic beta radiation normally requires radiochemistry to produce a pure and concentrated source of the nuclide of interest. The process normally involves dissolving the sample in concentrated acid, followed by chemical separation of the element of interest and terminating in the production of a thin electroplated source. This is counted, in vacuum, using a solid state detector with good spectrometric capability. The technique is capable of producing good results for nuclides at levels associated with environmental discharges and, hence, has probably excess sensitivity for levels associated with remediation.

There are other techniques using dissolution followed by solvent extraction and production of a plated source carrying the majority of both natural and man made α emitters. This source can then be counted and the nuclides present identified. The main problem with this technique is that the plating efficiency is very element dependent. Alternatively counting can be using liquid scintillation. These techniques reduce the cost per sample significantly at the expense of losing element selection. In some circumstances this can be an advantage, particularly if contamination is by a mix of elements, which would otherwise require several individual analyses. A further variation on the technique is to use barium sulphate precipitation on the solute followed by counting as a thick alpha source.

All these techniques derive their main advantage from the concentration they produce in the source and all are capable of making measurements at or below 0.1 Bq g^{-1}.

5.4.6 Radiochemical Analysis (beta emitters)

There are three common beta only emitting nuclides which might reasonably be encountered in a remediation exercise. These are strontium-90, carbon-14 and tritium-3. The first is normally found in equilibrium with its daughter yittrium-90 which is an energetic beta emitter and can be counted directly in bulk samples. However there are occasions where a specific analysis of strontium-90 would be required particularly where soil, for example, has a very high natural beta emitting level which could make estimation of the strontium-90 level difficult.

Establishing the strontium-90 level involves drying the soil, ashing it and then extracting the strontium-90 using boiling aqua regia (hydrochloric and nitric acid). This is processed to remove unwanted materials and the strontium-90 extracted either in an ion adsorption column or using fuming nitric acid. This process removes the yittrium-90. The sample is then normally stored to allow the yittrium-90 to return to equilibrium. The yittrium-90 is precipitated out and the resulting product counted using a gas flow beta counter.

Carbon-14 levels are determined very simply by drying the soil and then burning in a pure oxygen stream. The CO_2 produced can then be absorbed onto a material which is soluble in normal liquid scintillation counter cocktails. This can then be counted.

Tritium, as HTO, is also easily, but not particularly accurately, determined by adding water to a soil sample, stirring and then allowing the HTO in the sample to equilibrate with the excess water. A fraction of the water can then be measured in a liquid scintillation counter.

For organically bound tritium, the soil sample is normally dried and then burned in oxygen and the resultant water measured in a liquid scintillation counter.

For these nuclides levels likely to be associated with remediation exercises are far in excess of the minimum detectable activity which will allow a reduction in counting time and a higher throughput. The main problem with such measurements is the cost, generally £50 per sample upwards. More details are given in Table 5.3.

5.4.7 Unusual Techniques

Fissionable nuclides, particularly those which exhibit delayed neutron emission, can be estimated by subjecting samples to the intense neutron field in a research reactor to stimulate fission, removing samples into an efficient neutron counter, generally using ^{3}He detectors, and observing the decay of the resulting neutron signal. This method is particularly suitable where separated uranium, which is not in equilibrium with its decay chain, is possibly present.

5.5 Airborne Monitoring

Airborne monitoring is extremely useful when there is potential contamination of large areas of ground or where access at ground level is difficult. The technique is derived from geophysical exploration for minerals and uses extremely large volume sodium iodide scintillation detectors with volumes of 5 litres or more, giving extremely high sensitivity. Air attenuation has some effect, but is not a problem, as even a column 70 metres long, representing the line joining an aircraft at a height of 60 metres to an object 36 metres from the aircraft's ground reference, only represents a mass per unit area of 10 g cm^{-2}, giving a transmission for 1 MeV γ radiation of approximately 55%.

Typical backgrounds and sensitivities are such that a one second measurement is sufficient to identify levels of energetic γ emitters at, or in excess of, 0.1 Bq g^{-1} averaged over the area of view. This area tends to be ill defined because of the movement of the aircraft and because of the difficulty of collimating the extremely large detectors normally employed. There are also serious restrictions on low flying over built-up areas, with CAA exemption required for flying at a height of 200 feet.

This high minimum flying height also limits the spatial precision.

Aircraft can also carry large intrinsic germanium detectors for more precise spectrometry where the nature of the pollutant is ill defined. The performance of these detectors tends to be degraded slightly by the electrical noise and vibration encountered.

In summary airborne monitoring is extremely effective where large areas are to be monitored and where it is acceptable to present activity levels averaged over large areas of ground, i.e. of 0.25 hectares upwards.

5.6 Gate Monitoring

Some sites undergoing remediation or de-licensing are equipped with gate monitors, as are some disposal sites. These monitors are intended to identify vehicles which are carrying unacceptable radioactive material. The detectors employed are plastic scintillators, with typical dimensions of 1 m x 0.3 m x 0.1 m. Normally at least 4 are employed, two on each side of the vehicle. The vehicle is driven slowly between the pairs of detectors, normally at 3 miles per hour or less. The instrument then records and stores the count rate during the vehicle's passage. Two circumstances will cause an alarm. The first is where the count rate with the vehicle present exceeds the normal background count rate, which can be up to 2000 s^{-1}. The second is more subtle. Normally a load of inactive material will reduce the observed count rate when it passes between the detectors. The equipment will identify the possibility of a source or more active volume if the count rate shows a significant increase, perhaps not reaching normal background level. This increase can be caused by a void within the load, such as a large empty tank.

The sensitivity of the equipment is such that it can easily detect energetic gamma emitters at average levels from approximately 0.1 Bq g^{-1} upwards. For remediation exercises the alarm level may have to be set at a very high level, as soil levels leaving the site will be in excess of the remediation level, which itself is likely to be much in excess of 0.4 Bq g^{-1}. The high sensitivity of the unit also means that the detectors may alarm if the vehicle driver has been receiving treatment using ^{131}I for thyroid problems, for example.

5.7 Examples of Monitoring Techniques

The table below gives an indication of the methods which would normally be applied for the monitoring of the radionuclide stated at the activity level indicated. For some nuclides there is a range of monitoring methods available and it may well be that particular circumstances will dictate the use of other monitoring techniques.

The costs presented are per measurement. For in situ gamma these are based on recording the count rate for each 1 m^2 and for in situ beta on each individual measurement, both costed at a rate of £40 per hour. For the other measurements these are based on typical commercial rates for the counting and analysis together with on site costs of £40 per hour. More details on costs are given in Tables 5.2 and 5.3.

IB:	in situ beta
IG:	in situ gamma
IG(LE):	in situ gamma, low energy
RC:	radiochemical preparation
SA:	gross alpha counting of a sample
SG:	gamma sample

A useful point is that monitoring using the standard Mini Instruments 6-80 unit which is available to many local authorities is capable of identifying areas which would give typical occupier doses in excess of 400 μSv per year for the following nuclides and chains: cobalt-60, caesium-137, uranium-235, radium-226, neptunium-237 and thorium-229.

5.8 Definition of the Averaging Area, Criteria for the Detection of Small High Activity Areas and the Design of a Monitoring Programme

In most circumstances the averaging area can be defined in terms of the use of a particular area. For housing the obvious divisions are into house plots and access road and pavement areas. For these areas it will be possible to choose occupancy factors and to calculate, or measure, shielding factors and, hence, calculate maximum acceptable contamination levels. For sports fields obvious sub-divisions are the playing area, any spectator area and the changing area or pavilion. For larger areas such as earthworks, coastal defences and riverbanks, a habit survey will often be required to identify potentially highly exposed individuals, such as fishermen.

Often two maximum acceptable contamination levels are set. One is the average over the defined area and the other is the maximum acceptable level within that area, either based on activity per unit volume over a defined fraction of the original area or activity per object, where the contamination is mainly in terms of individual objects. The overall average is generally based on the calculated value of annual effective dose per unit activity concentration whereas the maximum acceptable level may be based on the maximum acceptable skin dose for an individual handling an active object.

Once these limiting values have been determined it is possible to design the monitoring programme. For walkover or vehicle surveys for γ emitters the process is relatively simple. For the overall average the maximum acceptable average activity level is converted into a corresponding instrument indication, normally μGy h^{-1} or counts per second. For areas of enhanced activity the same process takes place except that in this situation the time taken to traverse any area of the defined size has to be several times the reading interval of the ratemeter. For example, if the survey is based on a ratemeter indication with a time constant of 3 seconds then it must take in excess of 9 seconds to walk or drive along a strip of the defined area.

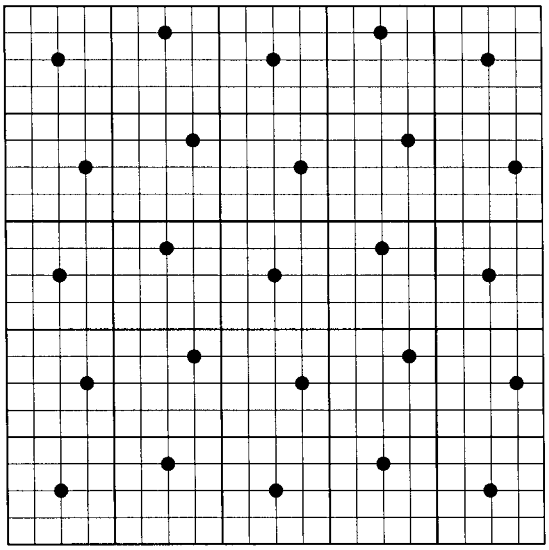
It may also be necessary to take account of the reduced solid angle subtended by the detector when dealing with the smaller area. For example, if it is assumed that the maximum acceptable averaging area is 4 m^2 then a square with sides 2 m viewed from a height of 1 m does not approximate to a semi-infinite source. This is because the detector can see both the area of interest and the area outside. In such a case it will be necessary to calculate a count rate corresponding to a 4 m^2 area at the maximum acceptable level, surrounded by a semi-infinite area of uncontaminated soil. If the count rate is below this calculated value then the area is acceptable. If it is above, then it may be acceptable if the surrounding area is also contaminated. This can be checked by scanning much closer to the ground, averaging the indication over the area specified and comparing the result with the limit for a semi-infinite source. This obviously takes longer.

The situation is possibly even more complicated when dealing with individual objects. In this case it is necessary to define a limiting object, i.e. one of a specified activity, buried at a specified depth. This value can then be converted, using the inverse square law and taking account of ground attenuation, into instrument count rates at specified distances. These values can then be folded with the proposed monitoring procedure to calculate the lowest maximum count rate value to be displayed by the instrument as monitoring takes place. This would be an object as far from the detector as possible. For example, using a 1 m pitch, no object on the ground would be more than 0.5 m from the walking line. If this count rate is not sufficiently elevated to draw the user's attention then it will be necessary either to change to a more sensitive instrument or to redesign the monitoring procedure to produce a denser, slower search pattern.

Monitoring by sample further increases the difficulty. The derivation of an average for an area is straightforward, even if the contaminant is relatively unevenly distributed. Typical values used to obtain good averages where gross non-uniformity (hot spots) is unlikely are from 10 samples upwards. The closer the measured values are to the limiting value for the area the larger the number of samples which will be required to demonstrate compliance. Section 8 of EPA (1997) (MARSSIM) deals with this in some detail.

For areas where hotspots are possible then the probability of failing to identify a hotspot becomes paramount. Ferguson (1992) deals with this in some detail. This paper includes a number of graphs illustrating the effect of sampling strategy and target areas shape and size on the number of sampling points required over a unit area, and the applicable level of confidence in the final success. For example, for a herringbone sampling strategy, where a target area of excess contamination is thought to cover 5% of the total site area, then at least 30 samples should be taken, where the aim is to identify the presence of a hotspot on 95% of occasions. As the acceptable averaging area for the hotspot declines then the number of samples goes up proportionally. For example, for a permitted hotspot averaging area of 1% of the original then 130 samples are required.

The choosing of a sampling grid is also important. Random samples give very poor results. Ferguson (1992) also mentions that, generally, the best results for randomly shaped potential hotspots are given by a herringbone measurement pattern (see below). An arbitrary starting point is selected and two axes at right angles set out.



Points are then selected at:

8ak, 8an
4a + 8ak, a + 8an
a + 8ak, 4a + 8an
5a + 8ak, 5a + 8an

where k and n have values of 0, 1, 2, 3 etc. The value of a is chosen so that reasonable coverage of the area is obtained. For example, for an area 50 m x 100 m a basic separation of 10 m would give good coverage and a good probability of identifying a hot spot of an area at least 3% of the total. This corresponds to a value of a of 1.25, and would give sampling points at the following locations for the following values of k and n.

	k=0, n = 0	k=1, n=0	k=1, n=1
8ak, 8an	0, 0	10, 0	10, 10
4a + 8ak, a + 8an	5, 1.25	15, 1.25	15, 11.25
a + 8ak, 4a + 8an	1.25, 5	11.25, 5	11.25, 15
5a + 8ak, 5a + 8an	6.25, 6.25	16.25, 6.25	16.25, 16.25

This can be viewed as setting out a base line from zero by moving 4 units forward, one to the right, 4 units forward, one to the left, 4 units forward one to the right, etc. From each of these points, at right angles to the original line, set out the same pattern, except that it starts 4 units forward, one to the left, 4 units forward, one to the right, etc.

This process can be continued until the whole area has been covered.

Samples should then be taken at, or near, the chosen sampling points and the results compared with the appropriate limiting levels. Again if the results are all demonstrably to one or other side of the limiting value then the conclusion is simple. The problem arises if the results are scattered on either side of the limiting value. Section 8 of MARSSIM covers this subject in some detail.

Plotting of the results on the site plan may allow the identification of a limited proportion of the area which is above the limit, which could then be remediated. These techniques are discussed in the following section.

5.9 Methods of Presenting The Results

5.9.1 Posting Plot

This is where the measured values are marked on the site plan in some way. This can be made more useful by banding the results and colour coding the plot. General variations and unusually active areas show up particularly well perhaps demonstrating, for example, that active areas correlate with particular features, such as roads, buildings or drains.

5.9.2 Frequency Plot

In this example the results are banded and displayed as a histogram. The plot shows any asymmetry in the results, where the maximum value is much higher than the mean, indicating a potential hot spot. Two peaks generally indicate the presence of an active and an inactive area and a very wide distribution generally indicates a wide variation of activity level throughout the area.

5.9.3 Calculation of The Mean, Standard Deviation and Median

The results are generally compared with the limiting acceptable value for the area under study. If all the results are below the value then the area is acceptable. Similarly if all the results are above the reference value then the area is unacceptable. If the results straddle the boundary of acceptability then the situation is more complicated as it is possible that the true answer for the area could lie above or below the reference value. Determining which is the case is a very much more complicated process and reference should be made to section 8 of Ferguson (1992).

The standard deviation is a good measure of the spread of the data. Comparison of the observed standard deviation with the statistical uncertainty expected from the larger than expected standard deviation indicates a wide variation in the range of the level of contaminant.

Comparison of the mean with the median also helps to identify data which is skewed. The median, defined as either the point or value for which 50% of the results are above and 50% below, should be subtracted from the mean. Differences which are small compared to the standard deviation indicate an unskewed distribution. Values which are large and positive indicate that the data is skewed towards the high end.

5.9.4 Mixtures of Radionuclides

In many situations only one radionuclide or decay chain is present, in which case presenting results in terms of Bq g^{-1} will be clear. However, where mixtures are present, particularly where the ratios of the various nuclide concentrations varies between samples, then it is normally efficient to present the results as an annual dose rate. This can be produced by comparing the measured activity concentrations with the values given in Table 5.1, or other appropriate values, and calculating the corresponding annual dose rate. These dose rates can then be summed to produce a value for each sample point. Where, for example, sampling has been performed to identify the levels of a pure beta emitter these calculated dose rates can be added to any directly measured gamma dose rate. Obviously the conversion from measured activity to dose rate assumes a semi-infinite volume, which will not normally be true, but it will serve to produce a readily interpretable site dose rate map to aid decisions on remediation.

5.10 Example Costs

Table 5.2 gives example costs for various forms of measurement based on existing UK practice and using a labour cost of £40 per hour. Table 5.3 gives costs for typical sample measurements using normal commercial rates.

Table 5.1 Examples of Monitoring Techniques

Nuclide or Chain Segment	Activity Concentrations for most Restrictive Land Use, Bq g-1 (see Section 6)		Lowest Cost Detection Method at Level Specified			
	10 mSv y-1	300 μSv y-1	10 mSv y-1		300μSv y-1	
			Method	Cost £	Method	Cost £
Co-60	9	0.3	IG	0.4	IG	0.4
Sr-90	10	0.3	IB	3	RC	240
Cs-137	42	1.2	IG	0.4	IG	0.4
Th-232	4	0.13	IG	0.4	SG	64
Ra-228	4	0.13	IG	0.4	SG	64
U-235	177	5.3	IG	0.4	IG	0.4
Pa-231	2	0.06	SG	64	SG	64
Ac-227	4.7	0.14	IG	0.4	SG	64
U-238	467	14	IB	3	IB	3
U-234	786	24	SA	124	SA	122
Th-230	196	5.9	SA	124	SA	122
Ra-226	11.5	0.34	IG	0.4	IG	0.4
Pb-210	4.2	0.13	IB	3	RC	240
Pu-238	60.7	1.8	SA	124	SA	124
Pu-239	55.8	1.7	SA	124	SA	124
Pu-240	55.8	1.7	SA	124	SA	124
U-236	860	25.8	SA	124	SA	124
Pu-241	3100	93	RC	240	RC	240
Am-241	65	2.0	IG(LE)	0.4	IG(LE)	0.4
Np-237	66	2.0	IG	0.4	IG	0.4
U-233	761	23	SA	124	SA	124
Th-229	19.6	0.6	IG	0.4	IG	0.4

Table 5.2 In-situ Measurements

Measurement	Time per Measurement (minutes)	Recording Time, if required. (minutes)	Pitch (m)	Coverage per hour (m^2)	Equipment Cost (£)	Cost per Hectare (£)
Air kerma rate using Mini 6-80	11	1	5	125	800	3600
Air kerma rate using Mini 6-80	11	1	5	125	800	3600
Air kerma rate using triple detector	6	1	5	214	1500	1800
Scintillation detector walk over	0.02	0	1	1800	1600	220
	0.02	0.5	1	110		3600
Hand held spectrometer walk over	0.17	automatic	5	1500	6000	270
Vehicle mounted scintillator	0.17	automatic	5	1500	50000	270
Vehicle mounted intrinsic germanium detector	1	automatic	5	60	60000	6700
Gross beta	3	1	5	100	1500	4000
Radon	30	-	per room	--	--	20 per measurement

Table 5.3 Measurements Requiring Laboratory Sample Processing

Measurement	Time to Take Sample (minutes)	Time to Process Sample (minutes)	Total Time per Sample (minutes)	Typical Cost (£)
Gamma spectrometry (low resolution)	10	45	55	64
Gamma spectrometry (high resolution)	10	45	55	64
Gross alpha	10	90	100	124
Radiochemical analysis (alpha)	10	180	190	240
Radiochemical analysis (beta, ^{90}Sr)	10	180	190	240
Tritium in soil	10	180	190	240

6. DEVELOPMENT OF A METHODOLOGY FOR ASSESSING AND CATEGORISING THE SIGNIFICANCE OF RADIONUCLIDES ON LAND IN INTERVENTION SITUATIONS

6.1 Introduction

The proposed radioactively contaminated land regime is specifically aimed at sites contaminated with radioactive materials which are not suitable for their current use and may be dealt with under the ICRP 'Intervention' case. The current planning regime will continue to deal with sites which will be subject to redevelopment.

Land may be contaminated with radioactivity because of activities carried out in the past (practices or disposal) or because of accidents involving radioactive material. There is a need for a practical methodology that can be used to categorise and assess radioactively contaminated land, and assist the determination of appropriate remedial actions. This Section reviews existing approaches for identifying radioactively contaminated land, compares them with approaches for non-radioactively contaminated land, and then proposes a methodology for identifying and assessing radioactively contaminated land.

The proposed approach is for contaminated land that is already in use when the contamination is identified, i.e. an intervention situation. The approach taken for contaminated land which is subject to change of use when radioactive material was identified as present would be different. In the latter case the future use of the land would be considered a practice.

6.1.1 Practice Situations

If the land is redeveloped, resulting in a change of use, new people would be exposed and the exposure pathways modified and this would be considered a practice situation under the radiation protection system proposed by ICRP. The remediation requirements will be linked to those of practices, i.e. dose assessment should be carried out of the prospective use, the results compared with dose limits and constraints and a decision taken on the extent of remediation required to meet the dose limits and constraints. Practice situations will not be considered further in this study.

6.1.2 Intervention situations

If the land is not subject to change of use when contamination was discovered, i.e. it is in use and its current use will continue, then the situation may be considered to be intervention. In this eventuality, the system of dose constraints and limits associated with practices do not apply. Instead, decisions on the degree and extent of intervention should be made by considering the remediation options and their effectiveness in terms of dose averted and other benefits and the practicalities and costs of their implementation. Estimates of the cost, disruption and harm should be balanced against the benefits such as dose saved and reassurance provided by the measure. Dose criteria for use in justifying and optimising the intervention strategies are given in Section 6.7.

6.1.3 Activities that are considered to be change of use

In the UK, significant change of use of land normally requires planning permission. The categorisation of land uses are given by the Use Classes Order 1987 (Table 6.1). This identifies the main uses of land and what changes can be made (permitted changes) without the requirement for planning permission. Therefore, if planning permission is being sought, the land can be considered to be undergoing change of use and this would be a practice situation. If planning permission is not being sought and radioactivity is present, the same or similar businesses and individuals would be exposed in similar ways and this would be considered an intervention situation. This approach does not adhere strictly to the ICRP recommendations, but gives a practical definition of intervention and practice situations.

6.2 Categorisation by Radiological Assessment

Three studies have been carried out by NRPB under contract that assess the radiological impact of various uses of land that are known to be contaminated by radionuclides. The areas of land were privately owned and hence access by members of the public had been restricted or prevented. The assessments estimated doses to populations exposed during the future redevelopment of land for use as housing and schools, commercial, recreation, agriculture, from development activity on a site and contamination of groundwater underlying a site. Contamination distributed uniformly over the ground surface, surface patches and buried contamination were included. Up to seven scenarios were considered, involving internal exposure from inhalation, inadvertent ingestion and consumption of foodstuffs, and external exposure from contamination were included in the assessment. The main features are summarised in Table 6.2. An estimate of annual dose and risk from potential future uses of the site was made and these are summarised in Tables 6.3 and 6.4. The results show that for uniform surface contamination, agricultural use of the land gives rise to the highest doses when summed over radionuclides. This occurs because of higher food production on the land, a more dusty environment and a higher outdoor occupancy. Housing use gives rise to the second highest dose; the dose from agricultural use is generally 50% higher than that from housing. Housing is important because of high occupancy and some food production on the land. Construction usually results in the third highest dose after housing and agriculture. This is due to the dusty environment and high inadvertent ingestion. Recreational use of the land gives rise to doses that are similar to construction (Table 6.4). Commercial use usually gives rise to lower doses due to low inadvertent ingestion of soil, low dust in air concentrations and relatively short, mostly indoor, occupancy. Drinking groundwater contaminated by the site consistently gives rise to the lowest dose.

Remediation levels from appropriate dose criteria were then derived. Whilst the assessment methodologies address practice situations (i.e. change of land use is expected to occur), the approach can be used to assess the doses and risks in intervention situations where no change of use is anticipated. Derived levels based on radiological criteria for intervention situations could then be used to categorise the land and to evaluate optimum remedial action.

Table 6.1 Summary of Use Classes for Land

Class	Description	Permitted change without planning permission
A1 Shops	Shops, retail warehouses, hairdressers, undertakers, travel and ticket agencies, post offices, dry cleaners etc, pet shops, cat meat shops, tripe shops, sandwich bars, show rooms, domestic hire shops, funeral directors	None
A2 Financial & professional services	Banks, building societies, estate and employment agencies, Professional and financial services, betting offices	To A1 where ground floor display window exists
A3 Food & drink	Restaurants, pubs, snack bars, cafes, wine bars, shops for sale of hot food	To A1 or A2
Sui Generis	Shops selling or displaying motor vehicles	To A1
Sui Generis	Launderettes, taxi or vehicle hire businesses, amusement centres, petrol filling stations.	None
B1 Business		
a)	Offices not within A2	To B8 (=<235 m^2)
b)	Research & development, studios, laboratories, high tech	To B8 (=<235 m^2)
c)	Light industry	To B8 (=<235 m^2)
B2 General industrial	General industrial	To B1 or B8 (=<235 m^2)
B8 Storage/Distrib	Wholesale warehouse, distribution centres, repositories	To B1 (=<235 m^2)
Sui Generis	Any work under the Alkali etc Work Regulation Act 1906	None
C1 Hotels	Hotels, boarding houses & guest houses	None
C2 Residential institutions	Residential schools & colleges, Hospitals & convalescent nursing homes	None
C3 Dwelling houses	Dwellings, small businesses at home, communal housing of elderly and handicapped	None
Sui Generis	Hostel	None
D1 Non residential institutions	Places of worship, church halls, Clinics, health centres, creches, day nurseries, consulting rooms, museums, public halls, libraries, art galleries, exhibition halls, non residential education & training centres	None
D2 Assembly & leisure	Cinemas, music & concert halls, dance, sports halls, swimming pools, skating rinks, gymnasiums, other indoor sports & leisure uses, bingo halls, casinos	None
Sui Generis	Theatres	None

Note: Changes between defined land uses within each subcategory (eg. A1) are permitted.

The Sui Generis land use categorises sit within each of the major land use clauses (e.g. A), but changes between land uses within the Sui Generis categories are not permitted without permissions, e.g. any development work (building, engineering or demolition) is not permitted.

Table 6.2 Review of Methodologies Assessing Doses and Risks from Radioactively Contaminated Land

Doc	Method/scenarios considered
NRPB Method	Dose assessment performed for exposures to **surface uniform contamination**, used to estimate dose and derive clean-up levels. 1) Exposure to site during recreational use, media: soil, age groups: Adult, child, infant, pathways: External, skin, inhalation, inadvertent ingestion. 2) Exposures at nearby school, media: soil, age groups: Adult, child, pathways: External, inhalation. 3) Exposure at nearby proposed housing estate, media: soil, age groups: Adult, child, infant, pathways: External, inhalation. 4) Contamination of groundwater, media: drinking water, age groups: adult, child, infant.
NRPB Method	Dose assessment performed for exposures to **surface uniform contamination**, used to derive clean-up levels. No dilution of activity. 1) Site development, media: soil, age groups, adult, pathways: external, inhalation, skin, inadvertent ingestion. 2) Commercial/industrial, media: soil, age groups, adult, pathways: external, inhalation, inadvertent ingestion. 3) Housing use, media: soil, age groups: adult, child, infant, pathways: external, inhalation, skin exposure, inadvertent ingestion, garden vegetables. 4) Agricultural use, media: soil, age groups & pathways: external (adult, child), inhalation (adult, child), skin (adult, child), inadvertent ingestion (adult, child), cereal, fruit ingestion (family). 5) Contamination of groundwater, media: drinking water, age groups: adult, child, infant.
NRPB Method	Dose assessment performed for exposure to **surface hotspot**: as uniform surface contamination, with dilution of activity for some pathways to 1% of original activity. Used to derive clean-up levels.
NRPB Method	Dose assessment performed for exposure to subsurface uniform contamination, 15 cm down. Used to derive clean-up levels. Disturbed & undisturbed contamination considered, dilution of conc when mixed with clean soil, activity conc down to 22%. 1) Site development, undisturbed, media: soil, age groups, adult, pathways: external 2) Site development, disturbed, media: soil, age groups, adult, pathways: external, inhalation, skin, inadvertent ingestion 3) Commercial/industrial, disturbed & undisturbed, media: soil, age groups, adult, pathways: external. 4) Housing use, undisturbed, media: soil, age groups, adult, child, infant, pathways: external 5) Housing use, disturbed, media: soil, age groups, adult, child, infant, pathways: external, inhalation, skin exposure, inadvertent ingestion, homegrown vegetables. 6) Agricultural use, disturbed, media: soil, age groups & pathways: external (adult, child), inhalation (adult, child), skin (adult, child), inadvertent ingestion (adult, child), cereal, fruit ingestion (family). 7) Contamination of groundwater, media: drinking water, age groups: adult, child, infant.
NRPB Method	Dose assessment performed for exposure to buried hotspot, 15 cm down. As for buried contamination above, undisturbed and disturbed hotspot considered. Disturbed hotspot dilutes conc to 22% in localised area. Used to derive clean-up levels.

Table 6.2 (continued) Review of Methodologies Assessing Doses and Risks from Radioactively Contaminated Land

Doc	Method/scenarios considered
NRPB Method	Dose assessment was performed using measured concentrations, uniform contamination, with elevated patches. 1) Site development, media: soil, age groups: adult, pathways: external, inhalation, skin, inadvertent ingestion. 2) Future users (industrial estate), media: soil, age groups: adult, pathways: external, inhalation.

Table 6.3 Estimated Doses from Different Land Uses (36 Radionuclides)

Rank: (most restrictive = 1) (note 2)	Activity distribution	Land use	Total dose (Sv y^{-1} per Bq g^{-1}) (See note 1)
1	Uniform surface	Agricultural	1.5 10^{-2}
2	Uniform surface	Housing	9.2 10^{-3}
3	Uniform surface	Construction	8.9 10^{-3}
4	Uniform surface	Commercial use	2.8 10^{-3}
5	Uniform surface	Drinking water	1.5 10^{-4}
1	Surface patch	Agricultural	1.7 10^{-3}
2	Surface patch	Housing	1.0 10^{-3}
3	Surface patch	Construction	5.0 10^{-5}
4	Surface patch	Commercial use	2.9 10^{-5}
5	Surface patch	Drinking water	1.7 10^{-9}
1	Subsurface area, disturbed	Agricultural	7.6 10^{-3}
2	Subsurface area, disturbed	Housing	4.6 10^{-3}
3	Subsurface area, disturbed	Construction	2.0 10^{-3}
4	Subsurface area, undisturbed	Construction	8.7 10^{-4}
5	Subsurface area, undisturbed	Housing	8.4 10^{-4}
6	Subsurface area	Commercial use	4.8 10^{-4}
7	Subsurface area	Drinking water	1.5 10^{-4}
1	Subsurface patch, disturbed	Agricultural	8.3 10^{-4}
2	Subsurface patch, disturbed	Housing	5.2 10^{-4}
3	Subsurface patch, undisturbed	Housing	2.5 10^{-4}
4	Subsurface patch	Commercial use	1.3 10^{-5}
5	Subsurface patch, disturbed	Construction	1.1 10^{-5}
6	Subsurface patch, undisturbed	Construction	4.3 10^{-6}
7	Subsurface patch	Drinking water	1.8 10^{-9}

Note 1: Total dose obtained by summing the dose per unit concentration of each of 36 nuclides. The nuclides are: H-3, Fe-55, Co-60, Ni-63, Sr-90, Tc-99, Ru-106, Cs-134, Cs-137, Ce-144, Pm-147, Sm-147, Sm-151, Eu-154, Th-232, Ra-228, Th-228, U-235, Pa-231, Ac-227, U-238, U-234, Th-230, Ra-226, Pb-210, Po-210, Pu-238, Pu-239, Pu-240, U-236, Pu-241, Am-241, Np-237, U-233, Th-229, Cm-244

Note 2: Total dose gives a measure of the most restrictive land use when summed over nuclides. However, the ranking may vary for individual radionuclides or for subsets.

Table 6.4 Estimated Doses from Different Land Uses (24 Radionuclides)

Rank: (most restrictive = 1) (note 2)	Land use	Total dose (Sv y^{-1} per Bq g^{-1}) (See note 1)
1	Agricultural	1.3 10^{-2}
2	Housing	7.6 10^{-3}
3	Construction	7.5 10^{-3}
4	Recreation + Nearby housing & school	4.0 10^{-3}
5	Commercial use	2.1 10^{-3}
6	Drinking water	1.4 10^{-4}

Note 1: Total dose obtained by summing the dose per unit concentration of each of 24 nuclides. The nuclides are: Co-60, Sr-90, Cs-137, Th-232, Ra-228, Th-228, U-235, Pa-231, Ac-227, U-238, U-234, Th-230, Ra-226, Pb-210, Po-210, Pu-238, Pu-239, Pu-240, U-236, Pu-241, Am-241, Np-237, U-233, Th-229

Note 2: Total dose gives a measure of the most restrictive land use when summed over nuclides. However, the ranking may vary for individual radionuclides or for subsets.

6.3 Alternative Categorisations

An alternative study (Vandenhove et al 1999) has been conducted for industrial activities and is included here for completeness. This study categorised land in terms of the industrial activity that led to the contamination, with the main route to man identified for each. Nine industrial activities were identified that could lead to contamination: 1) Uranium mining and milling, 2) metal mining and smelting, 3) phosphate industry, 4) coal mining and power production, 5) oil and gas drilling, 6) rare earth industries, 7) zirconium and ceramics, 8) disposal of building materials 9) radium luminising. This study also looked at remediation options and suggested a method for determining the optimum intervention strategy, using dose averted as the primary radiological criteria and intervention cost.

6.4 Methods for Assessing Non-radioactively Contaminated Land (CLEA)

A model (CLEA: Contaminated Land Exposure Assessment) has been developed which deals with chronic risks to human health and contains a number of generalised assumptions that have been used to develop UK guideline values for a range of land uses which indicate the need for soil remediation or more detailed site-specific risk assessment. CLEA focuses on pathways that could lead to direct risks to human health from specific site uses. CLEA is designed to evaluate the average daily intake of the contaminant via ingestion of soil, consumption of foods produced on the soil, skin contact with the soil and inhalation of dusts and vapours. CLEA does not model risks to the water environment, to construction materials or transient risks associated with site development. The method estimates intakes and body content of contaminants from six major land uses: 1) Residential with gardens, 2) Residential without gardens, 3) Recreational allotments, 4) Recreational and parks 5) Commercial for agriculture, 6) Other commercial uses. The approach is summarised in Table 6.5.

Table 6.5 Review of Methodologies Assessing Risks From Non-Radiologically Contaminated Land

Method/scenarios considered (CLEA Model/Method)

The system models non-radiological human health risks from contaminated land in various uses.
The following scenarios are considered:
1) Residential with gardens
2) Residential, without gardens
3) Recreational, allotments
4) Recreational, parks, playing fields
5) Commercial/industrial – horticulture and agriculture: (not yet available).
6) Commercial/industrial – all others, but excludes □fugitive dust□

Not covered: Effects of contaminated soil on groundwater, or transient risks associated with site redevelopment or construction.

Specific exposure routes (based on expected daily intake).
1) Outdoor ingestion of soil
   Main factor: soil ingestion rate g/d
2) Indoor ingestion of dust
   Main factors: 75% of dust = local soil, soil ingestion rate g/d
3) Consumption of homegrown vegetables:
   Main factors: the veg: potatoes, carrots, sprouts, onions/leeks, cabbage, salad, plus total intake of each, homegrown fraction, conc factor
4) Ingestion of soil attached to vegetables
   Main factor: fraction of vegetables weight that is actually soil.
5) Skin contact with outdoor dust
   Main factors: area of skin exposed, mass per unit area, duration
6) Skin contact with indoor dust
   Main factors: area of skin exposed, mass per unit area, duration
7) Outdoor inhalation of fugitive dust
   Main factors: Dust in air, (from: flux of suspended soil, wind speed, fraction of ground cover), breathing rate, occupancy.
8) Indoor inhalation of dust
   Main factors: Dust in air as per 7), breathing rate, occupancy.
9) Outdoor inhalation of soil vapour (organic contaminants only).
   Main factors: breathing rate, occupancy, conc in air (release of chemical from soil to air, release into the breathing zone, diffusion modelling).
10) Indoor inhalation of soil vapour (organic contaminants only).
   Main factors: breathing rate, occupancy, conc in indoor air (release of chemical from soil to air, release into the breathing zone, diffusion modelling).

CLEA calculates the expected daily intake, 18 age intervals used:
1-16 cover years 1-16 of life
17 cover years 16-59 of life
18 covers years 60-70 of life

Specify one of four averaging periods:
1) Lifetime average daily exposure over 70 y: Total intake over 70 y /70 y
2) Average daily exposure over < lifetime: Total intake over n y/70 y
3) Elapsed time average daily exposure intake: Total intake over n y/1 y
4) Unit time average daily exposure: Intake over 1 y/1 child y.

6.5 Comparison of CLEA and Radiological Assessment Methods for Contaminated Land

The approaches for assessing radioactively contaminated land and non-radioactively contaminated land are compared and contrasted. This comparison was intended to show whether there are any significant differences between the approaches. The two approaches are compared in Table 6.6.

Land use scenarios

The land use scenarios assumed by CLEA and the NRPB assessment approach are broadly similar, considering recreational use, housing, commercial use and agriculture. The radiological assessment method includes construction (site development), which is excluded from CLEA as CLEA does not consider this as a pathway for chronic exposure, and agricultural use, which is proposed for CLEA but not yet implemented. CLEA has additional land use scenarios: residential without gardens and allotments, and has additional exposures related to water pathways which are used as an alternative for calculating background exposure to contaminants through showering/drinking mains supply. In general the land uses are broadly consistent with each other. The land uses are also broadly consistent with those used by local authorities to classify land (Use Classes Order, Table 6.1).

Endpoints

CLEA calculates endpoints which are expressed as expected daily intake: EDI (mg of contaminant per kg of body mass). The EDI value is derived for a number of time frames and compared with reference values which present levels which offer risks of effects on the human body. The risks of effects are direct effects on health and, for carcinogenic substances, a cancer risk.

The radiological approach end points are the estimated annual dose from external and internal exposure and corresponding risk of fatal cancer.

Age groups

The CLEA model calculates the EDI for children, adults and the elderly. The EDI are derived for children in each of 16 age groups: 0-1 years, 1-2 years etc up to 15-16 years. EDIs for adults aged between 16 and 59 and the elderly between 60 and 70 years are also calculated.

The radiological assessment approach calculates annual doses to infants (1 years old), children (10 years old), and adults (18 years +). The age groups considered vary with the land use scenario. Doses to children and infants during site redevelopment are not calculated, because these age groups are not normally expected to be present.

Exposure pathways

In most cases, the CLEA model considers similar exposure pathways leading to intake of contaminants as does the radiological approach. The radiological approach includes a component of exposure arising from gamma emissions, which do not occur with non-radioactive contaminants. The common pathways are: inhalation of contaminated dusts and re-suspended soils, inadvertent ingestion of soil and consumption of foods produced on the land.

Data

In most cases the CLEA model and the radiological approaches use broadly similar data, although the principles of chemical toxicity and radiotoxicity are quite distinct in terms of how they are handled mathematically and in an exposure assessment context. Site occupancies are broadly similar, fractions of time spent indoors and outdoors by different age groups also agree. Human physiology (breathing rates) are based on similar models. The main difference is the estimate of inadvertent ingestion of soil. The CLEA approach implies annual inadvertent soil ingestion rates of up to an order of magnitude higher than those assumed in the radiological assessment and the rare phenomena known as pica (deliberate soil ingestion by young children) is included in CLEA for model completeness.

6.6 Implications of Differences in Approach Between Radiological and Non-radiological Assessment

The main implications of the differences in approach centre on the different endpoints and the higher inadvertent ingestion rates of soil used by CLEA. If the higher rates used in CLEA were adopted, the main effect would be to increase estimated doses where there are few exposure pathways and where the radionuclide gives rise to larger internal doses. This is therefore most likely to affect doses from alpha emitting radionuclides for commercial and recreational use of land. However, to maintain consistency with the critical group approach and data used in other radiological assessments, the approach for contaminated land was left unchanged.

Table 6.6 Comparison of Assessment Models for Radiologically Contaminated Land and CLEA Methodologies

Radiological assessment	**CLEA (non-radiological)**
Scenarios	
1) Recreational use of land	1) Recreational, parks, playing fields
2) Housing	2) Residential with gardens:
3) Site development activity	3) None
4) Commercial use	4) Commercial
5) Agriculture	5) Not yet included.
	Additional CLEA scenarios
	6) Residential, without gardens
	7) Recreational, allotments
	8) Background intakes: water
	9) Contact with water
	10) Vapour derived from mains water
Offsite scenarios	CLEA nearest
1) Groundwater	1) None
Endpoints	CLEA endpoints
1) Annual individual dose from internal exposure (Sv/y)	1) Expected daily intake (EDI) mg kg^{-1} per day, averaged over one of 18 time periods.
2) Annual individual dose rate from external exposure (Sv/y)	
3) Total annual individual dose (Sv/y)	
4) Annual risk from dose (/y)	

Table 6.6 (continued) Comparison of Assessment Models for Radiologically Contaminated Land and CLEA Methodologies

Radiological assessment	CLEA (non-radiological)
Age groups Infant, 1 y, Child, 10 y Adult >18 y	CLEA age groups Child, 0-1y, 1-2y, 2-3y, 3-4y etc to 15-16y, Adult, 16-59y, Elderly, 60-70 y
Exposure pathways considered (1,2,3: all scenarios, 4,6: housing, recreation, site development, agriculture, 5: commercial, 7&9: housing, 8&9: agriculture) 1) Inhalation outdoor – soil 2) Inhalation indoor – soil 3) External exposure – soil 4) Inadvertent ingestion outdoors – soil 5) Inadvertent ingestion indoors – dust 6) Skin contact (no absorption) – soil When foods are grown: 7) Home grown Vegetables 8) Ingestion of cereals 9) Ingestion of fruit	Exposure pathways considered (1,2,5,b,d) all scenarios, 4&6: all x commercial, 7&a: housing, allotments. 1) Inhalation outdoors - fugitive dust 2) Inhalation indoors - fugitive dust 3) Not applicable 4) Outdoor ingestion of soil 5) Ingestion of dust indoors 6) Skin contact with outdoor dust When foods are grown. 7) Home grown vegetables 8) None 9) None CLEA also considers the following a) Ingestion of soil on vegetables b) Skin contact with indoor dust Organics only: c) Outdoor inhalation of soil vapour d) Indoor inhalation of soil vapour
Habits & other parameters used: 1) Inhalation rates, NRPB age dependent standard physiology. 2) Inadvertent ingestion rates: age dependent: Infant: 2.5 g/y, pica: N/A, Child: 0.5 g/y, Adults: 0.25 g/y 3) Dust in air, ambient: 10^{-7}, disturbed: 10^{-6} or 10^{-5}, indoors 10^{-8} kg m^{-3}. 4) Home grown veg: Limited by garden area to 1/2 mean consumer. Potatoes = 25 kg/y. 5) Site occupancy: Commercial: 2000 h/y, Residential: 90%, outdoors: 10-20%	CLEA 1) Inhalation rates use reference man, ICRP-23 2) Age dependent inadvertent ingestion rates: 1-6y: 29g/y, pica: 150 g/y, 7-16 y: 22g/y, Adult: 9 g/y Dust in air: No value is given. 4) Home grown veg: not given by age group, Potatoes upper = 112 kg y^{-1} 5) Commercial 1955 h/y, Residential 66- 100%, outdoors, 16%

6.7 Methodology for Identifying, Assessing and Categorising Potentially Contaminated Land

The use of contaminated land may be considered to be an intervention situation or a practice. The status of the land can be established by determining if planning permission has been sought for the site. If planning permission has been sought then a change of use for the land is intended and the contaminated land situation is a practice, not an intervention, and the guidance offered in this work will not apply.

If planning permission has not been sought (i.e. the land will continue in its current use unchanged) then the situation is considered an intervention and the following method is proposed.

6.7.1 Dose and Risk Criteria Used In Intervention Situations

The dose criteria used in intervention situations have been discussed in 'Criteria for the Designation of Radioactively Contaminated Land', Ref DETR/RAS/99.010. Recommended dose criteria for justifying intervention strategies and for projected residual doses and the associated annual risks of fatal cancer (parenthesis) are given below:

- If the projected lifetime dose is in excess of 1 Sv, intervention is required (i.e. use of maximum effort, cost and resources is acceptable and high levels of disruption can be imposed). The most costly and disruptive of all interventions (permanent relocation) may be optimal.
- If the projected dose is above 10 mSv y^{-1} (risk $5x10^{-4}$ y^{-1}) intervention can be justified on risk grounds. The intervention strategy should be optimised on a site specific basis.
- If the projected dose is below 10 mSv y^{-1} (risk $5x10^{-4}$ y^{-1}) intervention will require justification and optimisation.
- If the projected dose is below about 300 μSv y^{-1} (risk $1.5x10^{-5}$ y^{-1}) intervention is very unlikely to be justified on radiological protection grounds alone.
- The intervention strategy should aim to reduce residual doses to below 10 mSv y^{-1} (risk $5x10^{-4}y^{-1}$).
- The intervention strategy should only employ costly or disruptive techniques if the dose averted > a few mSv ($1.5x10^{-4}$ y^{-1}).
- Assessment of harm and good arising from non-radiological protection issues may contribute to justifying intervention, and establishing the optimum intervention strategy.

Dose criteria represent the balance between the harm and benefit of an activity, and do not represent a boundary between safe and unsafe. The harm and good associated with intervention and hence the dose and risk criteria are set at different levels to those for practices and for non-radioactive contaminated land.

6.7.2 Proposed Approach for Assessing Land

The proposed approach for identifying, assessing and categorising radioactively contaminated land where no change of use occurs involves two main phases which can be considered as broadly comparable to Phase 1 and Phase 2 risk assessment as recommended in the DETR model procedures for chemically contaminated land.

i) Phase 1: initial screening assessment (= hazard identification and assessment)

ii) Phase 2: detailed assessment (=risk estimation and evaluation).

The initial screening assessment would be used to determine whether a detailed assessment was required and the priority for that assessment, or whether no further action was needed. If a detailed assessment was carried out, the assessment would be used to obtain a realistic assessment of the doses from the contamination for all expected activities on the land, and to provide the radiological protection basis for justifying intervention, and identifying the optimal intervention strategy.

6.8 Initial Screening Assessment

The initial screening assessment would involve 3 main stages: desk study, initial site survey and initial categorisation (screening), using the decision tree (Figure 6.1) and the screening levels in Tables 6.7 and 6.8.

6.8.1 Desk Study

Radioactive contamination of land currently in use may remain undetected for long periods of time. In particular, if the process that gave rise to contamination ceased tens of years previously, there may be little record of the industry or waste arisings. If radioactive disposals occurred on site they may not have been documented or the records may have been lost. Identification of the site as potentially contaminated may occur by chance, as a result of record searches if land were to be sold, or from studies of records carried out for other reasons.

If land is thought to be contaminated, the initial step would be to carry out a desk survey. The general approach taken for desk studies is given in Sections 4.2 to 4.5.

The desk studies should provide sufficient information to determine whether a monitoring survey is appropriate, and to provide input to the design of the studies so that the area to be surveyed can be identified. Any radionuclides thought likely to be present should be identified to assist those carrying out the survey to select the appropriate instrument type for detecting the expected radionuclides and to give some indication whether samples may need to be taken for laboratory analysis. If there is no evidence of contamination, a survey may be appropriate for reassurance purposes.

6.8.2 Initial Site Survey

A site survey would normally be planned using the results of the desk study. The approach taken for an initial site survey is shown in Figure 6.1.

Samples may be taken for laboratory analysis to confirm the site survey or if radionuclides are likely to be present that cannot be detected with field instruments (see Section 5.7 for examples of monitoring techniques for various radionuclides). The sampling strategy would take into account any information about the likely vertical and spatial distribution of radionuclides from the desk study and the results of the site survey.

6.8.3 Initial Categorisation (Screening)

The results from the initial site survey of the dose rate survey and activity concentration measurements are used to complete an initial categorisation of the site by comparing them with the screening levels and plotting an annual dose rate map.

The screening levels are in the form of a pair of activity concentrations (Bq g^{-1}) for 24 radionuclides that correspond to the dose criteria of 10 mSv y^{-1} and 300 μSv y^{-1} respectively (see 'Criteria for the Designation of Radioactively Contaminated Land', Ref 16022 rr 112, Section 2.3.3 for an introduction of dose criteria levels and Section 6.7 in this report for the basis for deriving the screening levels). Two sets of screening levels were derived. The first set (Table 6.7) are intended for uniform surface activity concentrations i.e. radionuclides widely and fairly uniformly distributed in the top 15 cm of soil. The second set (Table 6.8) are for surface patches and buried contamination, where radionuclides are distributed in the top 15 cm of soil over an area of less than about 20% of the site, or radionuclides are at depths > 15 cm (see Section 6.8.6). If the 10 mSv y^{-1} screening levels are exceeded a site-specific assessment is a priority. If levels are below the 0.3 mSv y^{-1} screening levels then a site-specific assessment is unlikely to be required as it is unlikely that remediation would be justified. Between the levels of 0.3 $mSvy^{-1}$, then a site specific assessment is a low priority, but may be beneficial.

The screening levels may be difficult to apply when a mixture of radionuclides are present and it may then be easier to use annual dose rates. Conversion factors for annual dose rates expressed as Sv per y per Bq per g have been presented for each radionuclide. For a mixture of radionuclides, the dose rate contributions should be added together to obtain the total dose rates and these results should be plotted to obtain a dose rate map of the site.

The initial assessment of the site may involve a site survey producing measured gamma dose rates. To incorporate measured gamma dose rate results and dose rates from the screening levels, all the results should be converted to annual dose rate using:

Annual dose rate (Sv y^{-1}) = gamma dose rate x (X x 0.01) x 8760

Where

Gamma dose rate = measured gamma dose rate (Sv h^{-1})

8760 = Number of hours per year

X = Percentage of the year site is occupied.

For 100% occupancy, a gamma dose rate of 1.1 μSv h^{-1} converts to an annual dose of 10 mSv and a dose rate of 0.03 μSv h^{-1} converts to an annual dose of 0.3 mSv. It should be noted that for dose rates below about 0.2 μSv h^{-1} variations in background level can make the estimation of the additional dose rate due to contamination less certain.

Table 6.7 Screening Levels (Bq G^{-1}) for 10 mSv y^{-1}(1.1 μSv h^{-1}) and 0.3 mSv y^{-1}, (0.03 μSv h^{1}) for Uniform Surface Contamination

Nuclide/Chain Segment	Most Restrictive Land Use 10 mSv y^{-1}, Bq g^{-1}	Most Restrictive Land Use 0.3 mSv y^{-1}, Bq g^{-1}	Dose per unit Concentration Sv y^{-1} per Bq g^{-1}
H-3	318.33	9.55	3.1×10^{-5}
Co-60	9.07	0.27	1.1×10^{-3}
Sr+90	9.73	0.29	1.0×10^{-3}
Cs+137	41.98	1.26	2.4×10^{-4}
Th-232	111.00	3.33	9.0×10^{-5}
Ra+228	4.33	0.13	2.3×10^{-3}
Th+228	12.04	0.36	8.3×10^{-4}
U+235	176.55	5.30	5.7×10^{-5}
Pa-231	1.98	0.06	5.1×10^{-3}
Ac+227	4.65	0.14	2.2×10^{-3}
U+238	466.67	14.00	2.1×10^{-5}
U-234	786.42	23.59	1.3×10^{-5}
Th-230	196.40	5.89	5.1×10^{-5}
Ra+226	11.47	0.34	8.7×10^{-4}
Pb+210	4.19	0.13	2.4×10^{-3}
Po-210	66.07	1.98	1.5×10^{-4}
Pu-238	60.70	1.82	1.7×10^{-4}
Pu-239	55.84	1.68	1.8×10^{-4}
Pu-240	55.85	1.68	1.8×10^{-4}
U-236	860.00	25.80	1.2×10^{-5}
Pu-241	3100.91	93.03	3.2×10^{-6}
Am-241	65.35	1.96	1.5×10^{-4}
Np+237	66.34	1.99	1.5×10^{4}
U-233	761.10	22.83	1.3×10^{-5}
Th+229	19.59	0.59	5.1×10^{-4}

Table 6.8 Screening Levels Related to 10 mSv y^{-1} (1.1 μSv h^{-1}) and 0.3 mSv y^{-1} (0.03 μSv h^{-1}), Surface Patches, and Buried Contamination

Nuclide/Chain Segment	Most Restrictive Land Use 10 mSv y-1, Bq g-1	Most Restrictive Land Use 0.3 mSv y-1, Bq g-1	Dose per unit Concentration Sv y-1 per Bq g-1
H-3	1591.67	47.75	6.3x10-6
Co-60	45.33	1.36	2.2x10-4
Sr+90	48.63	1.46	2.1x10-4
Cs+137	209.91	6.30	4.8x10-5
Th-232	555.01	16.65	1.8x10-5
Ra+228	21.64	0.65	4.6x10-4
Th+228	60.22	1.81	1.7x10-4
U+235	882.77	26.48	1.1x10-5
Pa-231	9.90	0.30	1.0x10-3
Ac+227	23.26	0.70	4.3x10-4
U+238	2333.35	70.00	4.3x10-6
U-234	3932.09	117.96	2.5x10-6
Th-230	981.99	29.46	1.0x10-5
Ra+226	57.35	1.72	1.7x10-4
Pb+210	20.93	0.63	4.8x10-4
Po-210	330.34	9.91	3.0x10-5
Pu-238	303.50	9.11	3.3x10-5
Pu-239	279.22	8.38	3.6x10-5
Pu-240	279.23	8.38	3.6x10-5
U-236	4299.98	129.00	2.3x10-6
Pu-241	15504.57	465.14	6.5x10-7
Am-241	326.74	9.80	3.1x10-5
Np+237	331.72	9.95	3.0x10-5
U-233	3805.48	114.16	2.6x10-6
Th+229	97.95	2.94	1.0x10-4

6.8.4 Screening Levels

The methodology for developing screening levels was based on existing NRPB work for assessing contaminated land performed under contract.

Calculation of Screening Levels for Uniform Surface Activity Concentration

Screening levels for each radionuclide and for each land use were calculated using the following formulae:

SL_{use} = DC/DPUC

Where:

SL_{use} = Screening level for the land use (Bq g^{-1})

DC = Dose criteria (Sv y^{-1}) 300 μSv y^{-1} and 10 mSv y^{-1}

DPUC = Effective dose per unit concentration from all exposure pathways relevant to land use (Sv y^{-1} per Bq g^{-1})

The exposure pathways considered for each land use are given in Table 6.6. The doses from each pathway were summed where appropriate to give the total dose to each age group (1 year old infant, 10 year old child and >18 years for adults). The maximum dose was then selected from all the land uses and age groups in order to obtain the most restrictive screening levels which are thus independent of land use.

The screening levels (SL) presented in Table 6.7 for use in initial site assessment were calculated from:

$$SL = \text{Min of } (SL_{use})$$

Hence the final screening levels are the most restrictive of the values for all the land uses. This means they are generic and conservative. The degree of conservatism included and the dose range spanned by the two sets of screening levels means that if neither screening level is exceeded then it is unlikely that the land is sufficiently contaminated to justify intervention on radiological protection grounds.

Calculation of Screening Levels for Surface Patches Occupying Less Than About 20% of the Area, Uniform Buried Contamination or Buried Patches (> 15 cm)

Screening levels for surface patches and buried contamination were calculated in the same way as for uniform surface contamination. However, it was assumed that either mixing with uncontaminated soil would occur, or that exposure to contaminated patches would be for less time than for uniform surface contamination. For buried contamination it was assumed that some disturbance could occur and some contaminated soil could be mixed into the uncontaminated surface soil. The degree of dilution for buried contamination may be significant, reducing the overall activity concentration by perhaps an order of magnitude or more. Burying contamination below clean surface soil can also significantly attenuate the doses arising from external exposure.

Initial screening is carried out over the area of the site to determine the area of contamination The screening levels for surface patches and buried contamination are shown in Table 6.8. It has been found from previous studies that the doses from surface patches and buried contamination were generally a lot less than a fifth of the uniform surface contamination dose. A screening level of five times the uniform surface contamination level was used throughout for screening levels for both surface patches and buried contamination. Using one multiplying factor keeps the number of different screening levels presented to a minimum and should simplify their use.

6.8.5 Progeny

During sampling and monitoring, ingrowth of radioactive progeny may need to be considered. Some radionuclides have progeny with fairly short radioactive half-lives (order of a few hours or days). In this case the progeny will reach secular equilibrium within a relatively short time e.g. less than 1 year. In these cases, the radioactive progeny have been assumed to be in equilibrium with their parent radionuclides in the calculation of the screening levels and conversion factors (Table 6.9).

In some cases, the progeny radionuclide have half lives of the order of a few to a few tens of years. In these cases, the extent of progeny ingrowth will be controlled by the time lapsed since the contamination process on the site ceased. Where sites were contaminated tens of years previously, the progeny of some radionuclides will have started to grow significantly

(Table 6.10). The site survey and sampling plans will need to take progeny ingrowth into account.

Table 6.9 Radionuclides for which Screening Levels Have Been Calculated and Progeny Considered to be in Secular Equilibrium

Nuclide/Chain Segment	Nuclides Included For Assessment Purposes
H-3	H-3
Co-60	Co-60
Sr+90	Sr-90 and Y-90
Cs+137	Cs-137 and Ba-137 m
Th-232	Th-232
Ra+228	Ra-228 and Ac-228
Th+228	Th-228, Ra224, Rn-220, Po-216, Pb-212, Bi-212, Tl-208 and Po-212
U+235	U-235 and Th-231
Pa-231	Pa-231
Ac+227	Ac-227, Th-227, Ra-223, Rn-219, Po-215, Pb-211, Bi-211 and Tl-207
U+238	U-238, Th-234 and Pa-234
U-234	U-234
Th-230	Th-230
Ra+226	Ra-226, Rn-222, Po-218, Pb-214, Bi-214 and Po-214
Pb+210	Pb-210 and Bi-210
Po-210	Po-210
Pu-238	Pu-238 (Pu-238 decays to U-234, shown above in the U-238 decay chain)
Pu-239	Pu-239 (Pu-239 decays to U-235)
Pu-240	Pu-240
U-236	U-236 (U-236 decays to Th-232)
Pu-241	Pu-241
Am-241	Am-241
Np+237	Np-237 and Pa-233
U-233	U-233
Th+229	Th-229, Ra-225, Ac-225, Fr-221, At-217, Bi-213, Po-213 and Pb-209

Table 6.10 Radionuclides Where Progeny Are Likely to Grow Insignificantly Over Tens of Years

Radionuclide	Progeny	Notes on Future Progeny Ingrowth Over Tens of Years
Ra+226	Pb-210, Po-210	Pb-210 & Po-210 will grow in significantly over tens of years, secular equilibrium with parent may be approached by about 80 years. Progeny ingrowth in locality may be affected by escape of variable amounts of radon gas from the soil. Parent activity not significantly reduced by radioactive decay.
Th-232	Ra+228	Ra+228 at or near secular equilibrium with parent within about 25 years. Parent activity not significantly reduced by radioactive decay.
Pb-210	Po-210	Po-210 approaches secular equilibrium with parent within 2-3 years. Parent activity will reduce by factor of 2 over 25 years.
Th-230	Ra+226, Po-210, Pb-210	Ingrowth not significant compared to parent over tens of years. However, radiological hazard from progeny may be significantly higher than parent. Secular equilibrium may take 10,000 + years to establish.
Pu-241	Am-241	Am-241 ingrowth peaks at around 75 years. Although Am-241 activity never exceeds 1/30th of starting activity of Pu-241, Am-241 presents 60 x greater internal radiological hazard. Parent activity halved by radioactive decay every 14 years.
Pa-231	Ac-227	Ac-227 will grow in significantly over tens of years, secular equilibrium with parent may be approached by about 80 years. Parent activity will not be reduced significantly over this time by decay.

6.8.6 Comparison of The Screening Levels With Measured Values

The derived screening levels for uniform surface contamination have been compared with measured activity concentrations from areas of the UK known to have high levels of radionuclides, either naturally (Table 6.11), from accidents or from past practices.

Table 6.12 shows that the measured concentrations are below the lower screening levels for uniform surface activity concentrations. This implies that none of the areas would need site specific assessment, implying that intervention would not be justified on radiological protection grounds.

Table 6.11 Comparison With Naturally Occurring Levels

Radionuclide	Measured Values Soil, Bq g^{-1},	Area	Upper Screening Level (Bq g^{-1})	Lower Screening Level (Bq g^{-1})
U-238	0.001-0.1	S. England	467	14
U-238	0.03-2	Cornwall	467	14
U-238	0.06-10	Scotland	467	14
U-238	0.016-0.17	Devon	467	14
U-234	0.06-10	Scotland	786	24
Th-232	0.001-0.18	UK	111	3.3
Th-232	0.022-0.069	Devon	111	3.3
Th-230	0.022-0.16	Scotland	196	5.9
Th-230	0.021-0.112	Devon	196	5.9
Pb-210	0.028-0.091	Devon	4.2	0.13
Pb-210	0.021-0.037	Berkshire	4.2	0.13
Po-210	0.028-0.117	Devon	4.2	0.13
Po-210	0.011-0.045	Berkshire	4.2	0.13
Ra-226	0.034-0.126	Devon	11.5	0.34
Ra-226	0.016-0.041	Berkshire	11.5	0.34

References: Bradley 1993, Ham et al 1998.

Table 6.12 Comparison with Fallout Affected Areas

Nuclide	Bq g^{-1}, 15 cm of Soil	% of Area Affected (approximately)	Upper Screening Level (Bq g^{-1})	Lower Screening Level (Bq g^{-1})
Cs-137	0-0.05	15 %	42.00	1.3
Cs-137	0.05-0.1	50%	42.00	1.3
Cs-137	0.1-0.15	15%	42.00	1.3
Cs-137	0.15-0.2	10%	42.00	1.3
Cs-137	0.2-0.25	5%	42.00	1.3
Cs-137	0.25-0.34	5%	42.00	1.3

References: Baker and Cawse: 1989.

None of the measured values of caesium-137 exceeded the lower screening level in Table 6.13. This implies that intervention is unlikely to be justified on radiological protection grounds. Farming restrictions are in force in very small parts of the area (post Chernobyl).

Table 6.13 Comparison with Areas Affected by Marine Discharges

Radionuclide	Measured Values Various Bq g^{-1}	Measured Values (FOE) Bq g^{-1}	Upper Screening Level Bq g^{-1}	Lower Screening Level Bq g^{-1}
Co-60	0.006-0.033	0.24-26	9.1	0.27
Cs-137	0.8-9.8	5.4-171	42	1.3
Th-232	0.06	-	111	3.3
Th-228	0.075	-	0.36	12.4
U-235	0.02	-	177	5.3
U-238	0.11-0.24	-	467	14
U-234	0.134	-	787	24
Th-230	0.5	-	196	5.9
Pu-238	0.06-1.8	-	60.7	1.8
Pu-239/40	0.18-9	-	56	1.7
Pu-241	7.8-18.6	-	3100	93
Am-241	0.5-12	5-11	65.5	2.0
Np-237	0.02	-	66.3	2.0
U-233	0.02	-	761	22.8

Cumbrian coastline and Ribble estuary, References: RIFE-3 1997, Rose et al 1995, HMIP 1994, Mudge et al 1994, Howarth 1992, FOE, 1989, Curtis et al 1991

Table 6.13 shows that the majority of measured values of radionuclides from around the Cumbrian coast and Ribble Estuaries are below the upper screening levels for uniform surface activity. However, the upper screening level was exceeded by a few measurements of cobalt-60 and caesium-137 reported by FOE from the Esk estuary. The majority of measured values of radionuclides are below the lower screening level for surface activity concentration. However, the lower screening level was exceeded by a small fraction of measured values of cobalt-60, caesium-137, plutonium-239, 240 and americium-241.

6.9 Site Specific Assessment: Intervention

6.9.1 Introduction

The need for a detailed site-specific assessment of radioactively contaminated land is identified from the initial categorisation of the land, as described in Section 6.7. The purpose of the site-specific assessment should be to establish a realistic estimate of doses from continued use of the site and to determine whether remediation is justified and the best option for remediation.

The detailed assessment activity is broken down into 2 main stages, 1) radiological assessment of current dose levels and projected dose levels and 2) assessment of the remediation options.

6.9.2 Radiological Assessment of Current and Projected Dose Levels

There are four stages in a radiological assessment:

i) An assessment of the radionuclides present, their spatial distribution and concentration in all relevant media, including radon in air inside and outside buildings and any foods produced on the site. Projected parent decay and progeny ingrowth over time frames of 50 years should be made. It is felt that over a 50 year time frame the effects of erosion across the site would start to become significant on the radioactivity in the soil. The time scale of 50 years is comparable to other prospective routine discharge assessments to air and land. Information may be available from the screening assessment. If not a re-survey will be required. Where groundwater may be affected by contamination on the site, projections of activity in groundwater over longer time frames should be considered

ii) An assessment of dose rates on the site, inside and outside buildings and above any covered areas, for example, areas that have been concrete covered or tarmac yards. Dose rates with background subtracted are required. This information may be available from the screening assessment. If not a re-survey will be required.

iii) Assessment of the needs and requirements of affected communities, in consultation with them. This should identify non-radiological issues, including the need for reassurance, political factors etc.

iv) An assessment of the use of the site and nearby land. This should address: habit survey of those on site, the occupancy of the site by individuals and groups, time spent above covered areas, indoor and outdoor occupancy and any unusual habits. An assessment of all feasible uses of the land which do not require planning permission and projected reasonable future habits should also be included for time frames of 50 years.

Two radiological assessments of the site should be carried out. Firstly, present day doses to site users and those on nearby land should be estimated using measured values of dose rates and activity concentrations in relevant environmental materials where available. The results of habit surveys should be used. Where measured values are not available, reasonable estimates should be made.

Secondly, a prospective assessment should be performed covering future periods of up to 50 years. Estimates of doses should be made, based on exposures arising from likely habits and current land use. Additional estimates of dose should be made for all reasonable habits that may arise from all uses of the land that do not constitute a change of use (changes limited to permitted changes of use). Permitted changes of land use are those changes to land use that do not require planning permission, as defined in the Use Classes Order (1987) (Table 6.1).

The dose assessments made should be realistic and based on the habit survey. Addition over exposure pathways should be performed as appropriate.

6.9.3 Assessment of Remediation Options

An assessment of remediation options and strategies should be made. This should address:

i) remediation options available.

ii) the effectiveness of the options at reducing activity concentrations and dose rates.

iii) the cost, disruption, hazard and any wider social and economic consequences of each of the intervention strategies.

iv) the appropriateness of the options, including practical aspects of application, waste arisings and disposal options for waste.

v) Justification and optimisation of the remediation options, leading to choice of remediation option.

The current day and prospective doses from continued use of the site and estimates of dose averted by each of the remediation options should be compared with the dose criteria for justifying and optimising intervention.

The dose criteria for intervention (Section 6.7) suggest that above projected annual doses of 10 mSv remediation is almost certain to be justified, whilst below projected annual doses of 0.3 mSv remediation is unlikely to be justified on purely radiological protection grounds. For more disruptive intervention options, annual doses of a few mSv or more should be averted. These dose criteria, together with an estimate of the practicalities and costs of the remediation and an assessment of the needs of the affected community should be used to determine the appropriate remediation strategy.

Cost benefit analysis may be carried out to give an indication of the optimum option. However, it may also be necessary to take into account wider social, political and economic factors such as reassurance, public acceptability, market values of land, any reduced utility either before or after remediation. No action may be optimum for doses of less than 10 mSv/y^{-1}.

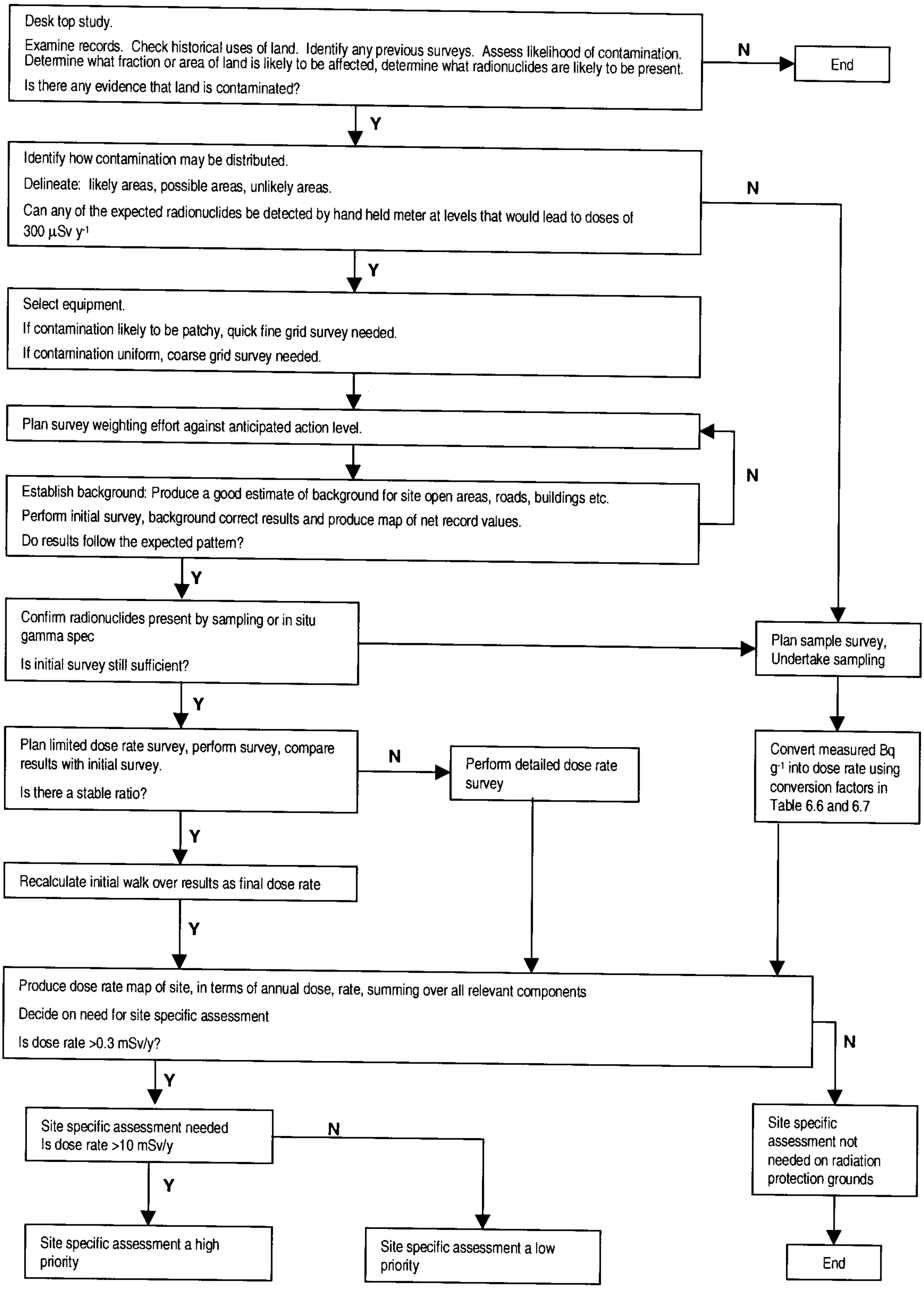


Figure 6.1 Decision Tree For Screening Land Containing Radionuclides

7. REVIEW OF REMEDIATION TECHNOLOGIES

7.1 Introduction

The method of remediating radioactively contaminated land most commonly used is excavation and disposal to a suitable landfill repository. Indeed, in the UK, this remediation method has been used almost exclusively as part of the strategy for managing soil material associated with unacceptably high levels of radioactivity. Whilst not offering the benefits usually associated with 'treatment' options, i.e. bringing about reductions in toxicity (in this case radiotoxicity), mass or mobility of the offending contaminants, long term disposal in secure landfill repositories has long been regarded as an acceptable solution to this difficult environmental pollution problem. In recent years in other parts of the world, notably the United States, other technologies have started to become established, or have at least undergone limited successful demonstration, to offer alternative remediation methods. Other, more innovative, technologies have the potential to provide full-scale remediation solutions but have not as yet been adequately developed and demonstrated. Most of these methods have emerged from developments with technologies introduced to deal with the wider issues of chemically contaminated land and, again, most of the applied R&D work has been undertaken outside of the UK. There are parallels between the conceptual approach to chemically and radioactively contaminated land remediation, and these are discussed in more detail in Section 1. In particular, the ICRP "Intervention" situation will influence the method of remediation selected for a particular site. Intervention must be "justified" and "optimised" with respect to the doses and costs, including social costs, to the critical group, particularly where the remediation of a site that has been completely redeveloped is contemplated. Historically, chemically contaminated land has often been remediated during a change of use; consequently, remediation technologies suitable for this kind of situation will be less relevant for the radioactive "Intervention" situation.

This Section provides a general overview of the broader array of established, demonstrated and emerging technologies for chemically contaminated land, including the classification of these technologies according to their mode or place of application, and the physical, chemical or biological mechanisms relied upon. It also identifies those technologies that have been applied to radioactively contaminated land problems with some success, as well as those that are regarded as having potential applicability; for the former of these two categories, fuller descriptions are given, special considerations are discussed, and specific strengths and weaknesses are identified. Recognising excavation and disposal as the established remedial method for radioactively contaminated sites, a fuller discussion of this method is presented, identifying key relevant issues. Consideration of opportunities for integrating remedial techniques is also given and an overview presented of indicative costs associated with the various techniques. In relation to decision making in the selection of remediation technologies, a generalised discussion of the steps to be taken in a systematic evaluation process is included and, finally, some specific considerations for the management of remediation activities are highlighted.

The key reference sources for this Remediation Technology Review Section are CIRIA (1995a), EA/DETR (in preparation), Martin and Bardos (1995) and Pearl (1997).

7.2 Remediation Technologies for Chemically Contaminated Land

7.2.1 Remediation and Risk Management

The procedure that has been developed in the UK for establishing what actions are required at a contaminated site, and for evaluating and selecting appropriate remedial measures or technologies, incorporates a risk management approach focused on modifying or controlling pollutant linkages (EA/DETR, in preparation) within the context of a source-pathway-receptor model. Risk management actions include any actions taken to control, reduce or eliminate the unacceptable risks identified at a site. They include remedial measures which involve direct action on the contaminants of concern or on their behaviour, as well as non-technical or administrative measures (institutional controls) where action involves the management of receptor behaviour to reduce/alter their ability to come into contact with the contaminants. Institutional controls can range from deeds and planning alterations to actual physical barriers, such as fencing around the site to control access. Risk management actions can be categorised as follows:

- Source control: technical action either to remove or in some way modify the source(s) of contamination;
- Pathway control: technical action to reduce the ability of a given contaminant source to pose a threat to receptors by inhibiting or controlling the exposure pathway(s) by modifying its/their characteristics;
- Receptor control: use of action or controls of a non-technical nature to alter the likelihood of receptors coming into contact with the contaminants e.g. by restricting access of receptors to the site, altering site layouts, changing land use, changing the point of water abstraction.

7.2.2 Classification of Technologies

Whilst there is no universally agreed classification for the methods used to remediate contaminated land, the classification system described here is based on the technical characteristics of the methods, and the ways in which they are applied in the field (CIRIA, 1995).

In this system the remedial methods are differentiated at a number of levels including mode of application (ex situ or in situ), media type, generic or proprietary status. The place at which remedial methods are applied, i.e. either on or off site, provides a further level of classification.

Two broad categories used to distinguish technical differences are 'civil engineering-based' methods and 'process-based' methods. The non-technical remedial measures referred to in Section 7.2.1 do not fall into either of these categories and are not included in the overview that follows. They will however be routinely evaluated in conjunction with technical measures and can form an important part of overall remedial strategies.

The classification adopted here for civil engineering methods is shown in Figure 7.1.

The two basic civil engineering approaches involved are removal (excavation) and containment using barriers. Both excavations and physical containment often need to be supported by hydraulic measures, either to control groundwater levels for practical purposes, or as part of the remedial operation itself. Civil engineering methods are classified according to the medium to which they apply and generically e.g. excavation and containment. In some cases further variations on these methods are possible.

Process-based methods are more complex to classify because of the range of different processes involved, possible modes of application and the number of generic methods and process variations available. The classification of these methods therefore involves more levels of differentiation, as shown in Figures 7.2. and 7.3.

Table 7.1 summarises generalised information on the applicability of a range of civil engineering - and process-based remedial methods for the treatment of contaminated soils/solids.

Table 7.1 Remedial Technology Applicability Matrix (Soils and Other Solid Media)

Remedial Method	Applicable Media[1]	Applicable Mode[2]	Applicable Contaminant Groups												
			Organic Contaminants								Inorganic Contaminants			Miscellaneous	
			VOCs	Halogenated	Non-Halogenated	PAHs	PCBs	Dioxins/ Furans	Pesticides/ Herbicides	Heavy Metals[3]	Non-metals	Asbestos	Cyanides	Corrosives	Explosives
Civil Engineering Approaches															
Containment – cover systems	S	E,I	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Containment – in ground barriers	S,W	I	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Excavation and disposal	S	E	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Biological based approaches															
Natural Attenuation	W,S	I	✓	✓	✓	x	x	x	✓	✓	✓	x	x	x	✓
Biopiles	S	E	✓	x	✓	✓	x	x	x	x	x	x	x	x	x
Bioventing	S	E,I	✓	✓	✓	✓	x	x	x	x	x	x	x	x	x
In situ Bioremediation	W,S	I	✓	✓	✓	✓	x	x	✓	x	x	x	✓	x	x
Phytoremediation	S	I	x	x	x	x	x	x	x	✓	✓	x	✓	x	x
Landfarming	S	E	✓	✓	✓	✓	x	x	✓	x	x	x	x	✓	x
Slurry phase biotreatment	S	E,I	✓	✓	✓	✓	x	x	✓	x	x	x	x	x	✓
Windrow turning	S	E	✓	✓	✓	✓	x	x	x	x	x	x	x	x	✓
Chemical based approaches															
Reactive walls	W	I	✓	✓	✓	x	x	x	x	✓	✓	x	x	✓	✓
Chemical dehalogenation	S	E	✓	✓	x	x	✓	✓	x	x	x	x	x	x	x
Soil Flushing	S	I	✓	✓	✓	✓	x	x	x	✓	x	x	x	x	x
Solvent extraction	S	E	✓	✓	✓	✓	✓	✓	✓	x	x	x	x	x	✓
Surface amendments	S	I	x	x	x	x	x	x	x	✓	✓	x	x	✓	x

Table 7.1 (continued) Remedial Technology Applicability Matrix (Soils and Other Solid Media)

Remedial Method	Applicable Media[1]	Applicable Mode[2]	Applicable Contaminant Groups												
			Organic Contaminants								Inorganic Contaminants			Miscellaneous	
			VOCs	Halogenated	Non-Halogenated	PAHs	PCBs	Dioxins/ Furans	Pesticides/ Herbicides	Heavy Metals[3]	Non-metals	Asbestos	Cyanides	Corrosives	Explosives
Physical based Approaches															
Dual Phase VE	S,W	I	✓	✓	✓	x	x	x	x	x	x	x	x	x	x
Air sparging	W,S	I	✓	✓	✓	x	x	x	x	x	x	x	x	x	x
Physico-chemical washing	S	E	✓	✓	✓	x	x	x	x	✓	✓	x	✓	✓	x
Soil vapour extraction	S	E,I	✓	✓	✓	x	x	x	x	x	x	x	x	x	x
Soil washing	S	E	✓	✓	✓	✓	✓	x	✓	✓	✓	x	✓	x	x
Electro-remediation	SW	E,I	✓	✓	✓	x	x	x	x	✓	x	x	✓	x	x
Solidification and stabilisation based approaches															
Cement and pozzolan based systems	S	E,I	x	x	x	✓	✓	x	x	✓	✓	✓	✓	x	x
Lime based	S	E,I	x	x	✓	x	✓	x	x	x	x	x	x	x	x
Vitrification	S	E	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	x
Thermal based approaches															
Incineration	S	E	✓	✓	✓	✓	✓	✓	✓	x	x	✓	✓	✓	x
Thermal desorption	S	E	✓	✓	✓	✓	✓	x	x	✓	✓	x	✓	x	✓

Table notes

[1] Applicable media (S) = Solid materials including soil and sediments, (W) = Ground and surface water.

[2] Applicable mode (I) = *In Situ* application, (E) = *Ex Situ* application.

[3] Generally applies to radioactive metals/radioisotopes.

(After EA/DETR, in preparation)

7.2.3 Overview of Technologies

The following sections provide a summary of contaminated land remediation technologies for chemically contaminated land that have been successfully demonstrated at full scale in either the UK, Europe or North America.

Civil engineering-based methods include:

- excavation;
- cover systems;
- vertical and horizontal in-ground barriers;
- hydraulic control measures.

Remediation by excavation and removal of the whole of the excavated contaminated soil to a suitably constructed landfill/repository is classed here as a type of civil engineering-based method in which in-ground barriers, hydraulic and gaseous emissions controls are used to contain the contaminants.

Process-based methods are separated into five generic categories, namely:

- physical systems;
- biological systems;
- thermal systems;
- chemical systems;
- immobilisation/solidification/stabilisation systems.

Within each of these five categories both ex situ and in situ processes are recognised. Ex situ processes are those which are applied to excavated soil either on site or off site. In situ processes occur in the ground, within relatively undisturbed soils.

The contaminated medium considered here is that of soil, although the remediation technologies reviewed have potential applicability to sediments and sludges as well as to solid materials often associated with soils, such as demolition rubble and fill material. Except for a brief review of hydraulic control measures, groundwater is not explicitly considered in this section, although some in situ process-based technologies for soils in saturated geological environments will offer some in situ groundwater remediation benefit. However, recognising that groundwater is an important medium that may be adversely impacted as a result of contamination leaching from overlying soils, a brief review of nuclear industry effluent processing technologies that have potential applicability to radioactively contaminated groundwater problems is presented in Appendix D.

7.2.4 Civil Engineering-based Technologies

Three basic approaches under this category are available:

- Removal (excavation) of contaminated material for treatment or disposal;

- Containment using barriers or covers to isolate contaminated material from specified targets;
- Hydraulic control measures, used in support of the above approaches, either as the primary means of control or specifically for the treatment of contaminated surface or groundwater.

Excavation

In the context of site remediation, excavation precedes one of the following activities:

- the disposal of excavated material off site at a suitably licensed landfill facility;
- the re-disposal of excavated material on site in a designated, suitably prepared and, where appropriate, licensed area;
- the treatment of excavated material at a suitably licensed facility either on or off site.

Excavation involves the controlled removal of contaminated soils, fills, sediments, sludges and construction debris from surface and below-ground locations. Excavated material may be transferred directly onto vehicles for transport away from the site or directed to a suitably prepared storage area pending removal, on site re-disposal or on site treatment.

Excavation is appropriate for removal of a wide range of contaminants provided that the soils, fills or other residues can readily be handled by conventional civil engineering plant such as hydraulic excavators, front-end loaders etc.

On Site Disposal

The disposal of contaminated excavated material on site at a suitably prepared and secure location may be carried out:

- where the volume of material involved is too large to be taken off site for disposal; where suitable disposal facilities do not exist; or where the material is currently not amenable to other forms of treatment;
- where, for a new development, part of the site is reserved for waste disposal purposes (possibly with a beneficial after-use such as parkland) in order to free the remainder of the site for construction purposes.

In both of the above situations, the siting and design of the on site repository will need to take into consideration the necessary risk reduction measures (such as engineered surface covers or caps, and planning restrictions) to protect human and other receptors from the contained contamination.

In general, on site waste disposal operations will have to conform with good practice for landfilling as set out in the relevant technical guidance. Thus the disposal of excavated material should take place only in a designated area of the site selected on the basis of the lowest long-term risk to public health or the environment. The disposal area must be suitably prepared to receive contaminated material, with appropriate measures taken to control water and, if appropriate, gas movement. Long-term monitoring of the disposal area is likely to be necessary in order that confidence may be gained in the integrity and performance of the repository. The on-site disposal of wastes may require authorisation by EA or SEPA under RSA '93.

Covering Systems

Covering involves the placement of a specified depth of 'clean' cover material over the surface of the contaminated ground, thereby protecting above-ground targets (occupiers, buildings, vegetation etc) from contact with underlying contamination. Depending on the depth of cover provided, building services can be protected by installing them within the cover layer.

In addition to this primary protective function, covering systems may be required to meet a number of other, sometimes conflicting, requirements such as:

- controlling water ingress and soil erosion;
- improving slope stability.

Although simple covering systems comprising a specified thickness of a single, relatively homogeneous material, can be used appropriately to deal with contaminated ground, engineered capping systems comprising more than one layer of different materials are necessary in some cases to meet a wider range of design and performance criteria.

In-ground Barriers

In-ground barriers physically isolate a contaminated mass of ground from the surrounding media (soils and water). In some cases chemical or other means may be used to create a barrier. Physical barriers may be used on a temporary basis (e.g. to prevent water ingress during excavation operations) or in a more permanent capacity to block the movement of contaminants over the long-term.

Several types of vertical barrier are potentially available (Table 7.2).

Table 7.2 Types of Vertical Barrier

Type of System	Example
Displacement systems	Sheet steel piling Vibrated beam wall Membrane wall
Excavated barriers	Secant walls Concrete diaphragms Shallow cut-off walls Slurry trench walls
Injection barriers	Chemical grouting Jet grouting Jet mixing Auger mixing Gel and polymer injection
Other systems	Chemical barriers Ground freezing Bio-barriers Electro-kinetic barriers

The construction of horizontal in-ground barriers for the containment of contaminated ground is less common than either surface or lateral containment, and horizontal barriers are generally regarded as being less reliable than other types. Four different approaches are in use:

- use of natural strata;
- permeation grouting;
- jet grouting;
- claquage grouting and hydrofracture techniques.

The latter relies on the injection of high-pressure fluid, often water, into existing fractures within a stratum. The excess of pressure creates further fractures within the material, and increases the pemittivity of the stratum, allowing more complete injection of grout.

The effectiveness and applicability of barrier methods vary according to the types and nature of contaminants present, physical conditions at the site, the design life of the barrier and the methods and materials used for construction purposes. However, barrier systems for isolation purposes, or to control the movement of in-ground gases and waters, are well established in civil engineering terms and may provide an economical solution in certain applications. (CIRIA, 1995a).

Hydraulic Measures

Hydraulic measures can play an important role in the remediation of contaminated land by:

- controlling the local hydrological regime to prevent or reduce contact between a contaminated ground mass, and surface and groundwater bodies;
- reducing or containing a plume of contaminated groundwater;
- supporting other remediation methods, such as excavation or physical barriers.

Several different approaches may be adopted for the management of the hydrological regime. These include the diversion of groundwater away from a contaminated land mass, and management of the discharge zone to prevent the release of contaminated groundwater into sensitive surface water bodies.

Hydraulic measures may also be used in conjunction with other remedial methods, such as physical barriers, to assist in separating the source of contamination from groundwater. Various combinations of barriers and pumping regimes are possible with the preferred configuration depending on site circumstances.

7.2.5 Process-based Technologies

Most process-based treatment technologies currently in use have been adapted from existing technologies used in oil and chemicals processing, waste treatment, or minerals processing. The use of process-based methods requires a good understanding of their chemical, physical and biological principles, as well as familiarity with the civil engineering operations involved.

Process-based methods can generally be applied both ex situ and in situ. In situ applications avoid the cost and potential health, safety and environmental impacts associated with the excavation of contaminated materials prior to treatment. In practice, ex situ methods have been used more widely because they allow the operator greater control over the process. Other advantages of ex situ systems include improved accessibility of contaminants to the treatment process and easier control over secondary emissions and process wastes.

The five generic forms of process-based treatment are:

- physical treatment methods;
- biological treatment methods;
- chemical treatment methods;
- thermal treatment methods;
- stabilisation/solidification.

Physical Treatment Methods

Physical processes do not destroy contaminants, instead they remove them from the soil (soil vapour extraction and electro-remediation) or separate the fractions of the soil which contain the contaminants (soil washing and, in radioactively contaminated land, detector based segregation). Physical treatment systems are thus volume reduction processes which can be applied:

- to reduce the amount of contaminated material requiring disposal to landfill or other repository or;
- as one stage of a multi-stage process, where the final stage of the total process is the destruction or immobilisation of the contaminants.

Physical systems include:

- ex situ soil washing, detector based segregation and batch electro remediation;
- in situ soil vapour extraction and electro remediation.

Soil washing systems separate contaminated and uncontaminated material by exploiting size, density, surface chemistry and magnetic differences between contaminants, contaminated soil particles and uncontaminated soil particles. Depending on the nature of the contamination and the matrix, separation may result in the segregation of differentially contaminated fractions (e.g. coarse and fine soil particles) or separation of the contaminants themselves (e.g. oil, metal particles) from the host material.

As a volume reduction process soil washing is limited by the proportions of the soil (size fractions) which are contaminated and which can be separated from the bulk soil, and by the costs associated with the disposal (or further treatment) of these fractions. Clay-rich soils also constrain the application of soil washing due to material handling limitations.

For some applications, physical soil washing processes are combined with chemical leaching or extraction to enhance the removal of contaminants from soil fractions. Chemical agents, which increase the solubility/mobility of targetted contaminants, include acids, alkalis, surfactants and complexing/chelating agents. The additional cost of reagents and process water treatment can however limit cost effectiveness of the process. These costs can be offset where the disposal cost of the contaminated soil is high, such as the case with radioactively contaminated soil.

Detector based segregation involves gross separation of contaminated and relatively uncontaminated zones of soils based on real time measurements of contaminant levels. This type of volume reduction is a 'dry' process that has been used mainly for radioactively contaminated soil where the main contaminant is a gamma emitter. Unlike soil washing, which separates the specific components of the soil which contain the contamination, detection based segregation is based on the gross separation of "batches" of contaminated soil from uncontaminated soil. Thus detection based segregation is ineffective where the soil has been mixed and homogenised.

Soil vapour extraction processes remove volatile contaminants from soils in the unsaturated zone by inducing, through use of vacuum pumps, negative pressure gradients around subsurface piped collection systems. The collected vapours (or off-gas) are transferred to on above-ground treatment or abatement unit, featuring technology such as activated carbon adsorption or biofiltration. The success of soil vapour extraction depends on the permeability of the soil and can be limited by subsurface heterogeneity and by natural or man made discontinuities.

Electro-remediation technologies exploit electrochemical differences between contaminants, contaminated soil particles, and uncontaminated soil particles. Typical processes feature an electrode assembly which either induces the controlled movement of desorbed complex ions through contaminated soils by electro-migration, or induces electro-osmosis of soil water in which contaminants are dissolved. These technologies can be effective in low permeability (clay-rich) soils but are strongly dependent on soil chemistry, particularly cation exchange capacity and pH buffering capacity.

Biological Treatment Methods

Biological treatment methods use the natural physiological processes of micro-organisms, such as bacteria and fungi, to transform, destroy, fix or mobilise contaminants (primarily organic contaminants). Biological remediation is potentially applicable to a wide range of organic contaminants and matrix types. The most commonly applied biological processes aim to breakdown organic contaminants into carbon dioxide, water and other simple inorganic compounds. Aerobic (in the presence of oxygen) and anaerobic (in the absence of oxygen) processes can be employed, and either natural indigenous, micro-organisms or specifically prepared biocultures (inocula) utilised.

As with other process-based technologies, both ex situ and in situ systems are available. Ex situ systems for soils, sludges and sediments may involve the use of engineered treatment beds, or dedicated reactors (slurry bioreactors) operating on a continuous or batch basis. Examples of in situ techniques which have had wide success in recent years are bioventing and biosparging. These systems typically involve, respectively, vacuum extraction of air through and from the unsaturated zone, and delivery ('sparging') of air to the saturated zone, targeting contaminated areas. With or without nutrient addition, biodegradation processes promoted by these methods can often account for over 80% of the measured contaminant removal, the remainder being attributable to contaminant volatilisation.

Because biological methods rely on the activities of living organisms, to be effective optimal process conditions must generally be established in terms of temperature, oxygen concentrations (or absence of oxygen), nutrient balance, pH etc. Effectiveness may be inhibited by the presence of certain contaminants, such as heavy metals.

As well as degradation processes, biological systems can also be used for the immobilisation and controlled mobilisation of contaminants and the accumulation of contaminants in plant biomass. Accumulation in plant biomass is a developing clean-up technology being applied to the remediation of heavy metal and radioisotope contaminants. Known as phytoremediation, this relatively slow, but low intensity and low cost method has tended to be used on soils with relatively low concentrations of contaminants which are widely spread and where the contamination is in the upper tens of centimetres of the soil (root zone). In this process certain types of plants, known as 'hyperaccumulators' (sometimes specially adapted), are used to translocate and concentrate the contaminants in their above ground tissue structure. This biomass can then be readily harvested and treated to remove the contaminants. A specific problem with this type of technique is the control of the destination of the biomass into which the contamination has been accumulated. This material should not enter a food chain, as transmission of radioactive material down the food chain may occur.

A further bioremediation technology variant which has specific application for metal contaminants involves the biochemically mediated conversion of contaminants to a less toxic and/or less mobile form. An example of this is a system currently under development (Kearney *et al*, 1997) where sulphur oxidising, acid producing, bacteria are used to induce leaching of heavy metals and radioisotopes from impacted soils as sulphates. The leaching step is followed by sulphate reduction using sulphate reducing bacteria in a bioreactor unit to yield insoluble metal sulphide precipitate.

Chemical Treatment Methods

Chemical processes use various types of chemical reactions to destroy or remove toxic compounds or to transform them into less toxic forms. Theoretically, a wide range of contaminants are treatable since chemical processes can be formulated to address particular contaminants. However, while many chemical based methods have been adapted to treat hazardous waste solids, there are relatively few documented examples of these being applied to contaminated soils. Treatments may take place by addition of reagents to either excavated soils, in their naturally occurring form, or soils suspended in a suitable liquid. Chemical reagents are typically added in excess to ensure complete treatment. Separation and/or further treatment of reaction products and residues may be required.

Unlike the situation with organic chemicals, the majority of inorganic contaminants (including heavy metals and radionuclides) are not amenable to destructive chemical treatments. Other kinds of chemical treatments are more appropriate for inorganics, including those which reduce their solubility and availability.

The range of chemical processes that can be used include:

- *Oxidation – reduction*
- *Extraction or leaching*
- *Dehalogenation*
- *pH adjustment.*

Oxidation reactions involve increasing the chemical valency of the toxic compounds. For example, many organic compounds can be oxidised to carbon dioxide and water (and are thereby destroyed) using chemical reagents. Under reduction reactions the valency of the toxic compounds is decreased, such as in the reduction of chromium (VI) to the less toxic and less mobile chromium (III). In adding oxidising/reducing agents to the soil, consideration must be given to the form of the contaminants (including intermediate compounds produced) during treatment.

Solvent extraction, though an established full scale technology is not commonly used as a stand alone treatment for contaminated soils, mainly due to cost. As mentioned above under 'Physical Treatment Methods', chemical leaching can be used to enhance the effectiveness of the physical separation and other processes in soil washing systems. An important issue for consideration with any application of solvent extraction is the handling requirements for the solvent (which may itself be toxic) and the possibility for residual solvent to be left in the soil after treatment. As well as use in ex-situ treatment systems, solvent extraction can be applied in-situ, although effective contact between the contaminants and the reagents can be difficult to achieve and control, and regulatory concerns over the effectiveness of capture of excess solvent/process residues represent a major limitation.

Dehalogenation processes under development include those involving zero-valent iron and other metals for use in the destruction of chlorinated solvents, and potassium glycolate (KPEG) which has been applied with some success to the treatment of high molecular weight PCBs.

Thermal Treatment Methods

Thermal treatment systems use elevated temperatures to remove, destroy and immobilise soil contaminants. The main types of thermal process recognised are:

- Thermal desorption;
- Incineration;
- Vitrification.

Thermal desorption is generally used for volume reduction and is a two-stage process. In the first stage, contaminants are volatilised from the contaminated soil matrix by temperatures up to around 600°C. This is followed by the second stage, in which the gaseous contaminant components from the first stage are either collected and concentrated using a sequence of scrubbing, filtration and condensation, or are destroyed by combustion at higher temperatures. It may be possible to re-use the treated soils following this process, depending on the residual concentrations of contaminants and the extent to which the original soil properties have been preserved. While established thermal desorption systems operate ex-situ, some more recently developed systems operate in-situ using injected steam or heated air to strip volatile components from contaminated soils.

Incineration involves the direct or indirect application of heat to contaminated soil, producing high temperatures (between 800 and 1200°C) that destroy the contaminants. Combustion gases are treated in the process to remove particulates and other combustion products. Since the process destroys the texture of, and removes the natural organic content from, the treated soils, they are usually unsuitable for subsequent use in supporting plant growth, but may be put to other beneficial uses, such as in construction material. A variation of this technique for the stabilisation of uranium and thorium is calcination, in which highly pyrophoric machining and casting swarf remnants, are calcined under controlled conditions to their oxides. This activity removes some of the more onerous measures required to prevent uncontrolled combustion (Ridal *et al*, 1998). This particular example appears to have been an isolated small scale trial for the stabilisation of a relatively small quantity of scrap material, and not a precursor to a larger plant.

Vitrification (which may also be viewed as a solidification/stabilisation technology) involves the use of high temperatures, usually over 1000°C, to destroy some contaminants and trap others in a glassy matrix formed from the contaminated soil. In Fellingham *et al* (1997), in-situ vitrification is to be used, by Geosafe, for the solidification and stabilisation of contaminated soil collected from over the Maralinga Test Site in Australia. The soil is to be disposed of in small pits, which will then be vitrified and capped. In the nuclear industry, vitrification is used to stabilise intermediate and high level wastes prior to storage, and may also be used to transfer liquid radioactive waste into a solid inert form (Lifanov *et al*, 1993), and so there exists an appreciable volume of expertise in this field. Varlakova *et al* (1998) describes an experimental ex-situ technique for the vitrification of radioactive waste incineration ash, which uses a "heating batch" addition to stimulate redox exothermic reactions which release sufficient energy, in the order of 5 MJ/kg, to melt the mix. Processing is on a batch basis in 100 litre crucibles, and produces an amorphous glassy matrix with low leaching rates.

Solidification/Stabilisation Treatment Methods

In addition to the technique of vitrification outlined above, stabilisation and solidification may achieve their objectives, including reduction of dispersibility and leachability, through a number of other techniques. Essentially, stabilisation and solidification are complementary, addressing the issues of both chemical and physical dispersibility:

- Stabilisation: addition of agents to form chemically immobile compounds of the contamination, such as the precipitation of heavy metals as insoluble sulphides or hydroxides;

- Solidification: addition to or processing of the contaminated soils to form a shaped mass which is physically strong, stable and resistant to leaching from natural agents, such as wind, rain and groundwater. No chemical interaction is required between the soil contaminants and the solidifying agents for solidification to occur.

Solidification/stabilisation may be carried out on both an in and an ex-situ basis, using the addition of common materials, including Portland cement, lime, pulverised fuel ash (PFA), clay, silicates, polymers and other additives, to react with metallic constituents to form insoluble compounds. These techniques are particularly suited to radioactive wastes, as they constitute containment systems, although their application in-situ could be complex and would rely heavily on closely controlled implementation.

Solidification is also performed in the nuclear industry to deal with radioactive liquid effluents such as boric acid waste, laboratory drain waste, incineration ash and spent ion exchange resin, and usually uses Portland cement to bind the constituents into a monolith (Nakashima *et al*, 1993). This can then be stored in an easily controllable form, such as the 500 litre stainless steel drums used in BNFL's Waste Packaging and Encapsulation Plant (WPEP). In the WPEP, effluent wastes are received, coarse filtered and pH adjusted before entering the 500 litre drum, into which is also injected the cementation agent. The mixture is homogenised and allowed to set (BNFL, 1997).

7.3 Potentially Applicable Technologies for the Remediation of Radioactively Contaminated Land

Of the remediation technologies described in Section 7.2.3 and summarised in Figures 7.1, 7.2 and 7.3, a limited number are considered to have potential applicability to radioactively contaminated land problems. Out of this select list, a small number have begun to establish a track record or have at least undergone limited successful demonstration in the field. These applicable or potentially applicable radioactive site remediation technologies are listed below under the major category headings previously defined.

Civil Engineering-based Technologies

Excavation and off site disposal	✓✓✓
Excavation and on site disposal/encapsulation	✓✓
Containment – cover systems	✓✓✓
Containment – in ground barriers	✓

Process-based Technologies (Ex situ)

Soil washing	✓✓
Physico-chemical soil washing	✓✓
Solvent extraction	✓
Surface (chemical) amendments	✓
Cement/pozzolan based solidification/stabilisation	✓✓
Non-cement based solidification/stabilisation	✓
Vitrification	✓✓
Electro-remediation	✓✓
Biologically-mediated conversion	✓

Process-based Technologies (In situ)

Soil flushing	✓
Reactive walls	✓
Cement/pozzolan based solidification/stabilisation	✓✓
Non-cement based solidification/stabilisation	✓
Electro-remediation	✓✓
Phytoremediation	✓✓

Key to stage of development:
✓✓✓ = Established technologies for RCL
✓✓ = Limited field demonstration/application
✓ = Emerging/potential technologies

Further descriptions of the above technologies (except emerging/potential technologies) are presented in the following technology summaries. These include commentary on some of the specific and relevant considerations for applying the technologies to radioactively contaminated land sites, and identify some potential limitations. Following the summaries, a more expanded discussion of the issues relating to the more common "excavation and disposal" option is presented. Finally, this section concludes with a guide to approximate costs for the alternative remediation technologies, including the identification of typical elements comprising a remediation scheme.

7.3.1 Potentially Applicable Techniques

A series of Technology Summary Sheets for the remediation technologies listed below are presented on the following pages.

Technology	**Technology Summary Sheet Number**
Civil Engineering Based Techniques	
Excavation and (on or off-site) disposal	1 and 2
Containment – cover systems	3
Containment – in ground barriers	4
Process-Based Systems (ex-situ)	
Soil Washing	5
Physico-Chemical Soils Washing	6
Cement/Pozzolan based solidification/stabilisation systems	7
Vitrification	8
Process-based systems (in-situ)	
Cement/Pozzolan based solidification/stabilisation systems (repeat)	7
Phytoremediation	9
Electroremediation	10

Owing to the lack of track record in the remediation of contaminated land using techniques apart from the traditional excavation and off site disposal, the costs given on the following summary sheets are of an indicative nature only. Where available, costs have been taken from sources dealing with the application of these technologies to chemically contaminated land. Consequently, when dealing with radioactively contaminated land, an increase in the unit cost is highly likely, given the increased health, safety, design and management requirements of such remediation.

TECHNOLOGY SUMMARY SHEET - 1	EXCAVATION

Technique Description:

As a precursor to ex-situ treatment, or as a treatment method in itself, excavation is usually carried out in a closely monitored manner. Contaminated media can be removed from the site, sentenced and segregated accordingly on a 'bucket-by bucket' basis, allowing confidence in the final remediation. RSA93 effectively applies as soon as a potentially radioactive material is excavated (i.e. becomes 'waste') for disposal, with attendant constraints. Frequently close regulatory involvement is required at all stages, including planning of a project.

The necessity for replacement material must not be overlooked.

Operational:

Consideration of several factors is required when planning an excavation exercise:

i) Creation of fugitive pollution sources;
ii) Monitoring for i) above;
iii) Nature and extent of contamination;
iv) Averaging volume of sentencing practice;
v) Regulatory requirements and involvement;
vi) Sequence of working and excavation plan;
vii) Replacement materials;
viii) Radiological Protection;
ix) Health and Safety.

Limitations:

Excavation is limited as a technique by the limitations of the equipment and, the quality of the initial survey, operational constraints (e.g. services, access), contaminant form and specific activity.

Treated Media:

Sand ✓ Silt ✓ Clay ✓ Peat ✓ Made Ground ✓ Sediments ✓ Groundwater X

Cost:	**Duration:**
Depends on quantity of material to be removed. Has been stated as £10.70/te (DETR/EA 1998) for chemically contaminated wastes and could be up to £40/te for radiochemically contaminated wastes.	Depends on access, form, nature and quantity. Anything to a year. (e.g. Old Dalby, [Macro, 1999])

References:

EA/DETR (in preparation).
Macro, (1999).

TECHNOLOGY SUMMARY SHEET - 2 | **OFF-SITE DISPOSAL**

Technique Description:

Depending on the activity concentration of the material, it may be disposed of to a number of different facilities. With the objective of removing the material from a situation where uncontrolled exposure is likely, to a controlled and engineered facility, off-site disposal is the preferred remedial method employed in the UK.

Operational:

The main advances in technology associated with off-site disposal involve the activity of segregation. Detector-based segregation allows the selection of various artefacts and heterogeneous media and their consignment to the optimum disposal route. This ensures that the finite resource of Drigg is efficiently utilised.

Drury (1995) details a gate monitoring system for the measurement and averaging of volumes of radioactive radium and thorium remediation wastes leaving a case study site. A large gantry was used with a number of sodium iodide scintillation counters arranged upon it to determine the average activity concentration of the material leaving the site, and ensure correct sentencing.

Landfill disposal is achievable for VLLW and exempt wastes under RSA '93. Disposal of wastes of higher activity concentrations to landfill sites can be negotiated with EA under a Special Precautions Burial Authorisation.

Limitation:

For activity concentrations outside those specified in the various Exemption Orders, material is consigned to Drigg or, for intense point sources, to a commercial concern. The Drigg resource is finite in that the facility has set activity and isotope licence limitations, as well as only accepting LLW materials.

Treated Media:

Sand ✓ Silt ✓ Clay ✓ Peat ✓ Made Ground ✓ Sediments ✓ Groundwater X

Cost:

Depends on specific disposal route negotiated. More information is contained in the Conditions for Acceptance for BNFL Drigg.

Duration:

Depends on access, form, nature and quantity. Anything to a year. (e.g. Old Dalby, [Macro, 1999]).

References:

Drury, (1995).

BNFL,(1999a) and BNFL (1999b)

TECHNOLOGY SUMMARY SHEET - 3 | COVERING SYSTEMS

Technique Description:

Covering involves the emplacement of a specified thickness of inert material over the surface of the contaminated ground. This material will thus isolate the contamination from receptors, and mitigate the associated exposure pathways, particularly the direct exposure of receptors to ionising radiation. Different materials have different attenuation capabilities (the use of concrete shielding is well known in the nuclear industry), and more specific design guidance on this aspect of the covering system may be gained from radiation protection literature.

The covering system may present additional benefits in terms of control of gas, leachate and groundwater egress and ingress, dust creation, erosion, stability and restoration potential.

Operational:

Several factors which require consideration include the following:

i) Identification and characterisation of contamination;
ii) Radiological assessment of suitability of covering as a restoration technique;
iii) Identification and characterisation of appropriate covering materials;
iv) Quality assurance throughout cover material emplacement;
v) Validation survey;
vi) Measures to prevent erosion of cover.

Limitations:

The principal limitation of covering as a restoration technique is that it imposes limitations on the future use of the site, in terms of user categories, built structures and any future civil engineering activity. There may also be a "blight" implication, with the remaining radioactive materials, despite their "safe" containment and the disposal may require authorisation under the RSA '93.

Treated Media:

Sand ✓ Silt ✓ Clay ✓ Peat ✓ Made Ground ✓ Sediments ✓ Groundwater ✓

Cost:	**Duration:**
Depends upon the design requirements. Has been stated as between £15 and £30 per square metre of ground covered (DETR/EA, 1998).	Depends on access, form, nature and affected area. Up to six months.

References:

Sutherland, 1999.
CIRIA 104.
EA/DETR (in preparation).

TECHNOLOGY SUMMARY SHEET - 4

IN-GROUND BARRIERS

Technique Description:

Many methods are available for the creation of physical or chemical barriers within the ground to control the movement of contaminants, while those most commonly used in the UK are sheet steel piling and slurry walls. The principal objective of the barrier is to control or alter the pathway term in the source-pathway-receptor relationship, and may do so by altering hydraulic conditions, preventing mobility and stabilising the ground, thus preventing physical erosion.

Operational:

The barrier is a civil engineering structure, and so consideration must be given to:

i) Character of contaminants and associated risk;
ii) Design criteria and design life of structure;
iii) Selection of suitable structure and methods for implementation;
iv) Site specific limitations, e.g. services, access, layout etc.;
v) Validation and long term monitoring;

Limitations:

Information on long-term performance of barrier systems is not widely available, while site-specific constraints may restrict the installation of the structure. The principal limitation is that the contamination remains in place, and so appropriate appraisal of the resultant risks and constraints on site use must be made. The contained contaminated may require authorisation under RSA '93.

Treated Media:

Sand ✓ Silt ✓ Clay ✓ Peat ✓ Made Ground ✓ Sediments ✓ Groundwater ✓

Cost:

DETR/EA, 1998, puts the costs at between £25 and £80 per square metre of trench installed for slurry walls, and £80 per square metre for sheet piling.

Duration:

Up to six months.

References:

EA/DETR (in preparation).

TECHNOLOGY SUMMARY SHEET - 5 | **SOIL WASHING**

Technique Description:

Extensive experience in the minerals industry of methods exploiting the physical characteristics of materials, and subsequent crossover with the environmental industry, has yielded a range of techniques for the separation of materials within a slurry matrix through the exploitation of their density and size. In this way, contaminants in free state, adsorbed onto a specific size fraction, or otherwise bound to the soil matrix may be removed, using a variety of methods including hydrocyclones, spiral separators etc.

Soil washing is operated as an ex-situ process based technique, using plant which may be assembled and operated on site. Following the creation of a suitable slurry, successive process stages subdivide the feedstream into various portions, which may then be disposed of or re-used on site, depending on their quality. Consideration must also be given to treating the process water, as this may become laden with contamination following use. Secondary treatment processes may be required to address the problem of contaminated process water and to render it fit for discharge or recycle.

Operational:

The primary factor controlling the use of soil washing is whether the soil matrix and contaminants are amenable to the process; for example, soils with high clay fractions are not amenable to soil washing, owing to the difficulty of creating a slurry. Other factors are as follows:

i) Nature and extent of contamination; soil washing is not economical for small quantities of contamination;
ii) Site layout and size;
iii) Location of services, in particular power and water supplies;
iv) Secondary process requirements, discharge restrictions;
v) Disposal and re-use routes for different process fractions;
vi) Excavation restrictions.

Limitations:

Soil washing can still be relatively expensive, and has a high specification for the feedstream. A large capital cost is also associated with plant, rendering it less suitable for small scale contamination, while its use for radioactive contamination would require careful decontamination of plant following use. The soil and contaminant distribution characteristics must also lie within a range suitable for exploitation, and present a reasonable volume reduction achievable through the process. A viable disposal route must be negotiated for the concentrated waste volumes and process water.

Treated Media:

Sand ✓ Silt ✓ Clay X Peat ✓ Made Ground ✓ Sediments ✓ Groundwater X

Cost:

Range of £20 to £160 per tonne of soil treated (DETR/EA, 1998). Resultant wastes and by-products may require further treatment and disposal.

Duration:

Up to 18 months.

References:

Martin and Bardos (1995), Pearl (1997), EA/DETR (in preparation).

TECHNOLOGY SUMMARY SHEET - 6	PHYSICO-CHEMICAL SOIL WASHING

Technique Description:

A very similar technique to conventional soil washing, physico-chemical soil washing utilises chemical additives to remove contamination as well as the particular physical characteristics of the contaminated media and the media-contaminant interactions. For example, chemical additives may be used in conjunction with an attrition scrubbing process phase to aid the desorption of contaminants from the soil matrix, while acid leaching may be used to dissolve and remove metals from the matrix. The key difference of this technology from conventional soil washing is that separated soil fractions may be treated with reagents as a batch or continuous flow process in a reactor.

Ionic surfactants may also be used to form a froth, which may then be processed through froth flotation to skim off contamination. Other metal treatment methods include chelating agents and mineral acids.

Operational:

As with conventional soils washing, although the process must include provision for the recovery of process reagents. Many such reagents may be undesirable or harmful if released as an effluent.

Limitations:

Fine-grained soils may require more intensive treatment owing to their greater surface area, and may present other handling problems. The process may also render the soils unsuitable for re-use as soils. The use of this technique for radioisotopes may also result in extensive contamination of process equipment, and may also result in the production of undesirable mixed waste, for example acidic liquor, which is not amenable to long-term storage.

Treated Media:

Sand ✓ Silt ✓ Clay ✓ Peat X Made Ground ✓ Sediments ✓ Groundwater X

Cost:	**Duration:**
Between £54 and £170 per tonne (DETR/EA, 1998). Resultant wastes and by-products may require further treatment and disposal.	Up to 18 months.

References:

EA/DETR (in preparation).

Martin and Bardos, 1995, "A review of full scale treatment technologies for the remediation of contaminated soil".

TECHNOLOGY SUMMARY SHEET - 7

CEMENT / POZZOLAN BASED SOLIDIFICATION / STABILISATION SYSTEMS

Technique Description:

An in-situ or ex-situ technique, solidification and/or stabilisation with cements or pozzolans may be performed with specialised soil mixing equipment or a process based mixing technique. The soil, once combined with the selected additive, may then exhibit superior hydraulic, physical or chemical characteristics, thus improving the overall quality of the ground. Additives include ordinary Portland cement, fly ash, silicates, organophilic clays and lime.

Operational:

The initial soil characteristics and the final desired characteristics should be appraised prior to developing a process mix design and commissioning a treatment. Consideration should also be given to the nature and extent of the contamination, the final use of the site, and the area to be treated.

Limitations:

The technique can be limited by certain hydrocarbons which interfere with the hydration of cement and its subsequent setting. Some contaminants, such as lead, are increased in solubility by the addition of cement. The heat of hydration of cement can also volatilise some VOCs and mercury. The technique also leaves the contamination in place, and so radioactive materials may not have their principal hazard mitigated, depending on the relative internal/external contribution to dose, although the potential for migration will be reduced and some attenuation of activity will take place.

Treated Media:

Sand ✓ Silt ✓ Clay ✓ Peat X Made Ground X Sediments ✓ Groundwater X

Cost:	**Duration:**
Between £17-85 per tonne of soil in-situ and £24-170 per tonne ex-situ.	Up to 18 months.

References:

EA/DETR (in preparation).

TECHNOLOGY SUMMARY SHEET - 8 | **VITRIFICATION**

Technique Description:

This technique can be used either in-situ or ex-situ, and uses heat to melt and solidify contaminated media. The main advantages are that vitrified material is very resistant to weathering, and thus the mobility of the contaminant is reduced. The system has been used in the USA to vitrify transuranic contamination, although it will not alter the direct hazard of exposure to the material.

DETR/EA (1998), details a UK system which uses a glassmaking furnace to treat contaminated soil in-situ, treating contaminated soil with additives to aid the process. The molten vitrified media is then cooled to form blocks of material.

In-situ systems may use an electrical potential across the contaminated volume to heat it to the required temperature, although problems can be encountered over the constitution and homogeneity of the material, as well as the potential for off-gas creation and collection. Such a system is detailed in Fellingham *et al* (1997), where extensive surface contamination over the Maralinga nuclear test site was collected and buried in debris pits. These will then be vitrified, while one in-situ vitrification has already been carried out on a trial basis.

Anecdotal evidence suggests that the vitrification technique has had a number of operational problems and consequently conditions have not permitted full implementation of the technology in the field.

Operational:

The process is very energy-intensive, as temperatures can reach over 1500 degrees centigrade. In addition, various gases will be produced within the furnace which will require careful treatment to permit their discharge to atmosphere. Consequently, large plant is required, and so the system is often best used ex-situ, except for large volumes of waste.

Limitations:

The considerable quantities of energy and cooling water required, coupled with the large amount of plant, require a large ground area for the process plant. It is thus not economical for the technology to operate for small volumes of contaminated material. The feedstream must also be controlled with respect to substances which could produce undesirable compounds in the off-gas, such as chlorine and phosphorous, and large quantities of organic matter. There is known to be the potential of explosion during the vitrification process.

Treated Media:

Sand ✓ Silt ✓ Clay ✓ Peat X Made Ground ✓ Sediments ✓ Groundwater X

Cost:

Has been stated as between £30-£50 per tonne for fixed facility costs, excluding transport, in Europe, and £520 per tonne for on-site plant (DETR/EA, 1998).

Duration:

Up to six months, depending on the type of process, as in-situ vitrified material may take a long time to cool fully.

References:

EA/DETR (in preparation).

Fellingham, Butter, Parker, 1997, "The rehabilitation of the former British nuclear weapons test site at Maralinga in South Australia", BNFL STAR seminar, April 1997.

TECHNOLOGY SUMMARY SHEET - 9

PHYTOREMEDIATION

Technique Description:

Abbott (1997) gives a broad overview of the various techniques and target substances for phytoremediation. Potentially applicable techniques, as they relate to plant types/physiology include the following:

- Hyperaccumulators, or plants which will actively accumulate metals, can used for the removal of contaminants from slightly or moderately contaminated soils (Martin and Bardos, 1995), although their use for actinide removal is not reported. The paper suggests that "halotolerance" in plants will allow high tolerance to alkali metals;

- Moderate Accumulators: the hyperaccumulator *Thlaspi caerulescens* for ^{90}Sr, potential for U in crop plants, grasses and herbaceous plants for ^{137}Cs;

- Phreatophytic Trees: uptake of ^{244}Cm, ^{137}Cs, ^{238}Pu, ^{226}Ra, ^{90}Sr by several species;

- Rhizofiltration: accumulation of ^{137}Cs and ^{90}Sr by Hydrocotyle and Sr++ by *Lemna minor*, U(VI) and Sr ions by *Helianthus annus*.

The paper compares phytoremediation with other technologies, mentioning that phytoremediation is likely to contribute most to sites where the contamination is in near-surface non-leachable form. The cost of phytoremediation is lower than more conventional techniques, although the treatment timescale involved is often long. The technique can also generate large volumes of secondary waste (in the form of harvested vegetative matter), although this is thought to be much lower than the primary waste generation of conventional techniques after "ashing".

The issue of food chain accumulation of radioelements accumulated into biomass must be addressed as part of the health and safety considerations within a phytoremediation project.

Operational:

This potentially applicable technique is a very long-term measure, and this requires other management techniques to control risks in the short-term. Because of this long operational term, initial capital costs may be comparatively low.

Limitations:

The treatment of mixed wastes may present a problem in terms of phytotoxicity or low uptake of substances other than the target radioactive material, requiring consideration of other remediation technologies to operate contemporaneously.

Treated Media:

Sand ✓ Silt ✓ Clay ✓ Peat ✓ Made Ground ✓ Sediments ✓ Groundwater ✓

References:

Abbott, 1997, "Phytoremediation: A promising technology (in the cleanup of radioactively contaminated sites)", BNFL STAR seminar, April 1997.

TECHNOLOGY SUMMARY SHEET - 10	**ELECTROREMEDIATION**

Technique Description:

Electroremediation can be operated as an in-situ or ex-situ "batch" process, which is essentially a modified version of the in-situ process. Three stages are involved; the desorption of contaminants from the soil, the movement of these contaminants through the soil matrix and pore water to electrodes, where they can be captured and removed.

The system relies on the burial of a range of electrodes across which a DC current is applied. This desorbs contaminants either through an "acid front" created by the hydrolysis of water at the anode or by the controlled movement of complex ions from additional solutions. Contaminants then move to the electrode housings by electromigration or electroosmosis, where they can either be pumped from the ground in aqueous form and subsequently treated or captured on solid sorbents which may be recovered and disposed of later. Housings have porous walls through which the contaminants may pass, into a purge solution for transport to the surface.

Operational:

The technique requires substantial borehole construction in which electrodes, housings and suitable solute treatment plant can be inserted, as well as above-ground treatment facilities if the aqueous solute recovery version is to be used. It is one of the few technologies suitable for silt and clay soils. Ex-situ techniques will require the construction of a number of treatment "cells" to treat the solute on a batch basis.

Heavy metals and other inorganics such as arsenic, polar organics, volatile organic compounds and some radionuclides (especially ionic form) are all suitable for remediation using this technique.

Limitations:

Near-commercial applications are limited to heavy metals and inorganics such as cyanide.

Treated Media:

Sand ✓ Silt ✓ Clay ✓ Peat ✓ Made Ground ✓ Sediments ✓ Groundwater ✓

Cost:	**Duration:**
Not available	Dependent on adsorption rates, contaminants and extent of contamination.

References:

Pearl (1997), Martin and Bardos (1995),

7.3.2 Excavation and Disposal of Radioactive Materials

Since excavation, segregation and off-site disposal is the most common remedial strategy employed in the UK, this section considers in more detail the factors that need to be considered in implementing this approach. Key issues to consider are :

i) Risk management and Minimisation

ii) Remedial End-Point

iii) Sentencing and Segregation

iv) Averaging Volume

v) Validation.

Risk Management and Minimisation

Prior to commencing site works it is essential that detailed consideration is given to the risks that the works may pose to current site occupants, remediation operatives, adjacent residents and future site workers. The properties of the contaminating isotope(s) influences the nature of the risk and detailed protocols are necessary to ensure that risks are managed and minimised during the works. These will need to be presented and agreed with the relevant regulatory bodies; Environment Agency and the Health & Safety Executive. In general the principles of ALARP should be applied i.e. keeping the risks "As Low As Reasonably Practical".

Regulatory compliance must be considered with regard to the radiological protection of the remediation operatives, site occupants and the general public (under the Ionising Radiation Regulations 1985).

Remediation End-Point

In determining an acceptable remediation end-point for the concentration of the contaminating isotope consideration needs to be given to the following :

- future use of the site
- residual risks to users from the proposed end-point
- definitions of radioactivity in RSA '93
- UK guidance on acceptable dose rates.

Segregation and Sentencing

The remediation protocols for segregation and sentencing will need to be designed around the defined waste categories under the Radioactive Substances Act 1993 and subordinate exemption orders. The disposal routes normally available include :

- Free release of material below RSA thresholds i.e. return to site as uncontaminated.
- Landfill disposal of exempt wastes (Under RSA '93).
- Landfill disposal of wastes under a Special Precautions Burial

- Disposal of low level wastes at BNFL Drigg
- Intermediate Level Waste (ILW) to storage pending availability of disposal routes.

For waste disposal it is often the case that landfill routes are difficult to establish and disposal to Drigg may be restricted. Drigg has a limit on the total activity of each radioisotope that it may accept in any one year (e.g. radium-226 - 30GBq/year) and as such delays can result and interim arrangements may be needed for the safe temporary storage of such materials.

The presence of chemical contaminants should be taken into account as, dependent upon the licensing condition of the landfill, these may prohibit the use of some sites.

In sentencing the waste the properties of the contaminating isotope and the soil matrix are important considerations in identifying the most appropriate site monitoring equipment and laboratory analytical methods. The success of a particular monitoring technique may be greatly influenced by the attenuation of radiation within the matrix and the geometric positioning of the source. Accuracy and cost are also important considerations.

For off-site transport wastes should be packaged in compliance with the Radioactive Materials (Road Transport) (Great Britain) Regulations and in compliance with the disposal site requirements. Specific arrangements can be made at, for instance, the receiving landfill site in order to manage the potential hazard associated with the wastes. These can include minimising workers exposure to the waste and ensuring that the waste is capped on the day of disposal to minimise any future exposure. For disposals of low level wastes to Drigg strict conditions for acceptance including packaging requirements are prescribed by the operator, BNFL.

Averaging Volume

In correctly sentencing waste materials a critical consideration is the representative activity concentration for a given volume of waste. This is referred to as the averaging volume and is not defined in any UK legislation or regulatory guidance. Since radioactive contamination is often heterogeneous in nature i.e. distributed discrete point sources, the remediation proponent is faced with an important decision on what is an acceptable averaging volume. This decision needs to be considered on a case by case basis and agreed with the regulator. It will be influenced by:

- the properties of the contaminating radionuclides;
- the feasibility and cost of monitoring and segregation;
- the availability of appropriate disposal routes for particular waste streams;
- the risks to remediation workers handling the materials;
- the consequences in terms of risks to the public of materials retained on the site which, although having a low average specific activity, may contain ‘hot spots’.

In practice averaging volumes established in the UK have typically ranged between 0.1 m^3 to 10 m^3.

The activity concentration of each ‘volume’ of waste can be determined in the field by direct probe measurement calibrated for the contaminating isotope and confirmed by sampling and laboratory radiochemical analysis. Typically each volume is removed by means of a mechanical excavator, sentenced using the prescribed analytical technique and consigned on disposal.

Validation

During remediation works operations should be continuously assessed as part of the operating protocol against the achievement of the remediation end-point. Following remediation a validation survey should be undertaken to demonstrate compliance with the remediation objectives. The validation survey will typically be based on a programme comprising a walkover survey, trial pitting and radiochemical analysis. Validation methodologies are discussed in Section 5.8. The intensity of the survey will depend upon the assessed potential residual risk, the characteristics of the contaminating isotope, the distribution and homogeneity of contamination on the site and the sensitivity of the end use. A typical validation survey will include a 100% walkover survey and trial pitting on a grid of 25 m x 25 m down to undisturbed ground.

The validation survey will be an important element of any final completion report for the remediation works which will aim to provide the necessary documentation to demonstrate achievement of the remediation objectives and to provide reassurance to site users and confidence to future site owners of purchasers in the status of the site.

7.3.3 Technique Integration

Whilst radioactively contaminated sites may exhibit a relatively narrow and homogenous profile in terms of the nature and activity of the radioactive constituents present, other kinds of contaminants (i.e. inorganic or organic chemicals) will often be found to exist in some radioactively impacted areas. Remedial methods, particularly process-based methods, will generally be unable to deal effectively with the full range of contaminants present in these cases and there may be a need to combine different methods at the same site.

In some situations there may be benefits in applying treatment technology to separate inorganic contaminants from organic contaminants, as an initial step in a 'treatment train'. For example, removal of radioactive, toxic metals from a mixed waste stream may render remaining organic contaminants amenable to ex situ bioremediation. In some cases it may be possible to use integrated technologies to treat different contaminant groups simultaneously The treatment of mixed wastes is a broad topic in its own right, and there is much experience in the United States of the segregation or treatment of radioactive and hazardous wastes, arising from the decommissioning of Department of Energy sites. A specific example of this expertise is given in Biyani *et al* (1998), which describes experimentation with resin immobilisation of mixed wastes.

Careful consideration should be given to the evaluation of remedial options to identify methods which may have the potential to integrate effectively with others to fully address contamination-related objectives.

7.3.4 Indicative Costs

Several references exist on indicative costs of remediation technologies. However, as the principal technology employed in the remediation of radioactively contaminated land is excavation and subsequent sentencing of the excavated material for disposal or replacement, little financial data is available for projects featuring alternative remediation technologies.

The cost of a remediation project consists of a number of components. A breakdown of typical cost elements is outlined in Table 7.3.

Some of the remediation technology summary sheets given in CLR 11 give approximate costs for various technologies when applied to chemically contaminated land (EA/DETR, in preparation), while Pearl (1997) also gives a selection of cost ranges for various techniques (Table 7.4).

Table 7.3 Cost Elements in a Remediation Project

Cost Element	Examples
Site Preparation	Hardstanding for mobile plant, access, site services, site accommodation
Regulatory Approvals	Prior approval for project, monitoring, waste management licensing, planning consent, discharge permits, safety case
Equipment	Pre-treatment, any processing plant, post-treatment handling, pilot scale tests, treatability studies
Mobilisation and start-up	Transport and assembly of any plant, calibration, QA procedure establishment, supporting equipment.
Health and Safety	Provision of RPS and equipment, as required, PPE
Fixed costs	Contingency, insurance and taxes, fees.
Labour costs	Fees and expenses – Designer/Project Supervisor/Contractors
Consumables	Treatment Agents, Maintenance supplies
Utilities	Fuel, water, electricity
Pollution Control measures	Collection and treatment of any effluents, periphery monitoring
Waste disposal	Any process residues, pollution control wastes, remediation wastes
Analysis	For process control, monitoring, sampling, compliance and validation
Maintenance	Modification of any process plant, maintenance of health and safety provision, long-term monitoring
Demobilisation	Decontamination of plant and area (and monitoring of such), disassembly of any process plant etc.
Reporting and aftercare	Fees, any incidental expenses, Public Relations issues

After CIRIA (1995a) and Pearl (1997)

These cost elements should be considered to build a cost for the entire remediation project - the costs given for each technique on the Technology Summary Sheets refer to the unit cost of the remediation technology only.

Table 7.4 **Indicative Costs for Various Applicable Non-Radioactively Contaminated Land Remediation Technologies**

Category	Ex-situ/ In-situ	Treatment Technique	Indicative Cost - £/tonne
Physical	Ex-situ	Soil Washing	20-160 (higher for radioactively contaminated soil)
		Detector based segregation	
		Batch electroremediation	N/A (estimated approximately 40-70)
Biological	In-situ	Phytoremediation	
Chemical	Ex-situ	Soils washing by chemical leaching	50-100 (up to 250) (higher for radioactively contaminated soil).
		Solvent extraction	75-600
		Dehalogenation	15-430
	Ex-situ and in-situ	Reduction/oxidation	not available
	In-situ	Soil flushing	25-85
Immobilisation/ Solidification/ Stabilisation	Ex-situ	Solidification/Stabilisation – pozzolan and cement systems	15-60
	In-situ	Solidification/Stabilisation – pozzolan and cement systems	60-110
Thermal	Ex-situ	Vitrification	5-520
	In-situ	Vitrification	220-550
Containment systems and hydraulic measures		Cover systems	20-30/m^2 of land
		Vertical barriers	Displacement barriers 80/m^2, Excavated barriers shallow and deep slurry walls (30-60 and 60-120 /m^2
		Horizontal barriers	200/m^2

Note: Depending on radioactive species etc., it is likely that significant multipliers will be applicable to some of these costs.

Owing to the lack of well-defined track record of techniques applied specifically to radioactively contaminated land, the above costs are indicative only for non-radioactively contaminated land. It can be assumed that, owing to greater hazards and controls associated with radioactive contamination, costs for treating such material will be higher.

If the material, however treated, is to be disposed of to the BNFL site at Drigg, the disposal costs have a number of components. According to Tothill and Tuck (1998), disposal costs consist of:

- A volume charge;
- A containerage charge;
- An activity charge.

Such that disposing of 16 m^3 of soil contaminated with radium and thorium will attract a £27 000 volume charge, a charge for the provision of ISO containers of around £10 000, and an activity charge of around £48/MBq activity disposed. Total disposal charges will vary according to specific volumes, activities and container requirements. In addition, BNFL publish Conditions of Acceptance for Drigg; these impose certain conditions on the type and form of waste accepted (BNFL, 1999a and 1999b).

7.4 Evaluation and Selection of Remediation Technologies

7.4.1 Introduction

Selection of a preferred remedial strategy should represent a balanced judgement on which of the available remedial measures (or combinations thereof) offers the most cost-effective and technically satisfactory solution against the objectives defined for the remediation work. The evaluation and selection process should allow for the specific site conditions and receptor circumstances, the estimated costs and benefits achievable, the governing regulatory framework, and the aspirations of the involved stakeholders, to be considered together and an acceptable balance struck. In practice, given that the conventional approach to the management of radioactively contaminated land in the UK is heavily biased towards "change of use" situations and landfill disposal of unacceptably contaminated soil materials, and given the lack of experience with alternative remediation technologies, the evaluation and selection approaches adopted will inevitably be non-exhaustive and fairly limited until the barriers to the use of new and more sustainable technologies is overcome. The following paragraphs discuss the identification of site-specific remedial objectives to focus the process for selecting appropriate remedial technologies and strategies, and briefly cover the approach that may be taken to formally evaluate and compare the options initially identified to provide a logical and reliable basis for selection decisions. For complex cases, particularly where multiple contaminants or a range of waste types are present, reference should be made to guidance providing more comprehensive coverage of remedy selection procedures (e.g. EA/DETR, in preparation).

7.4.2 Remedial Objectives

As a principle, the remedial or risk management objectives that should take priority in determining the type of remedial action to be taken should be contamination-related objectives, which relate to the acceptable residual risks associated with specific contaminants under a defined site end use scenario. In practice, engineering and/or management objectives may also have to be met, and there may be additional site-specific constraints to consider (such as the presence of unstable ground or the proximity of residential development).

As the selection process develops these objectives and constraints play an important role in determining which of the possible remedial options can be considered. Nevertheless, it is important that the contamination-related objectives guide the selection process.

Contamination-related Objectives

Contamination-related objectives derive from an assessment of the doses or risks presented by the contaminants on the site. The assessment may have a qualitative or quantitative basis depending on the available data and the specific contaminants of concern. The objectives will address:

- critical exposure route(s) and target(s);
- acceptable contaminant levels, or range of levels, for different site areas depending existing or proposed use or function.

In practice, it is important to express remedial objectives in specific and, if possible, quantitative or comparative terms. This allows a more precise definition of remedial requirements, and a better appreciation of both the technical and financial implications of any remedial action.

Quantitative contamination-related objectives are typically expressed in terms of that level of residual contamination (equating to a defined acceptable level of dose or risk) permitted on the site following remedial action. Objectives may refer to residual levels of radioactivity in:

- near surface or replacement materials (e.g. for direct contact hazards to children, building materials);
- growth media in landscape areas;
- soils in the unsaturated zone where these represent an ongoing source of groundwater contamination.

Other indirect criteria may have to be set to ensure contamination-related objectives are met. Examples include radioactivity attenuation properties and the maximum permitted permeability of a containment system, or the radioactive emissions levels and concentrations of contaminants in the leachate from a contaminated soil matrix having undergone stabilisation/solidification treatment.

Engineering Objectives

The improvement, maintenance or modification of the engineering properties of the site may be an important aspect of the remedial action. However, there may be some degree of conflict between contamination-related objectives and those relating to the engineering properties of the site. For example, the need to drain an area for construction purposes should prompt consideration of how a change in the redox condition is likely to affect the nature or behaviour (particularly the mobility) of the contaminants. Contaminated material (e.g. large deposits of incinerator ash) may also constrain foundation design or options for improving poor load-bearing characteristics.

Changes in engineering properties of the treated material should be considered. For example, soil washing processes change the physical properties of soils by separating out fine and coarse-graded fractions. This may present problems for re-use in some applications.

Only by addressing such objectives at the earliest possible stage in the selection process can the advantages of integrated remedial/geotechnical measures be achieved and potential conflicts avoided.

Management Objectives

Management objectives relating to both the site remediation activities and the results achieved by remediation should be defined and considered alongside other objectives. Examples of management objectives are as follows:

Objectives for Remediation Activities

Regulatory compliance

Remediation treatment within specified budget.

Remediation treatment within specified time frame.

Remediation treatment to be feasible under existing site conditions and using available services.

Remediation technology to provide a sustainable solution.

Remediation ensuring a satisfactory level of public confidence in the end result and a consequent avoidance of "blight".

Post Remediation Objectives

Compliance with regulatory requirements.

Compatibility with continuing or intended land use.

Minimum post-treatment requirements (e.g. monitoring, maintenance).

Compatibility with intended land use/management arrangements.

Avoidance of long-term legal liabilities.

Ease of transfer to new owner, although not strictly an objective from the viewpoint of the new regime.

Acceptability to funding and insurance bodies.

7.4.3 Technology Selection

Depending on the complexity of a site contamination problem, the technology or remedy selection process may include a number of steps and involve evaluation against many factors in order to systematically narrow down a wide field of candidate technologies and identify the most suitable remedial strategy or strategies. Such strategies may involve several technology combinations to address different site contamination issues. Conversely, for less complicated sites where, for example, there exists a very limited range of contaminants affecting media possessing fairly consistent characteristics, the selection process will be relatively straightforward involving relatively few steps and a limited number of initial candidate technologies. Unless radioactive contamination co-exists with other kinds of chemical contaminants that will require remediation and/or is present in a variety of forms affecting a variety of media (soil) types, then it can be reasonably assumed that remedy selection for radioactive sites will be a relatively short and simple process. The shortage of viable generic technology options at present, serves to reinforce the validity of this assumption.

However short and limited the technology selection process, the focus of the initial screening of remedial methods (including, if applicable, process options) should be very much on the identified remedial objectives (particularly contamination related objectives). The initial screening should also rely primarily on data which are readily available from site investigation and assessment, together with the technical and practical experience and information available to those undertaking the selection process. However, it may be necessary to resolve technical uncertainties relating to promising or favoured remedial methods through extended site investigation works and/or appropriate treatability testing

Depending on the intended rigour of the technology evaluation and selection process, a set (or sets) of evaluation criteria will need to be devised. These criteria or key factors should address the general characteristics, capabilities, requirements and limitations associated with each potentially applicable method in relation to the particular circumstances at the site. A typical list of such key factors is as follows:

- Applicability of technology;
- Long-term effectiveness and permanence;
- Cost;
- Availability/development status/reliability;
- Practicality, including timescale;
- Short term disruption and impacts;
- Operational requirements;
- Local Community and Institutional Acceptance.

In a formal evaluation exercise, weighting methods are often employed in conjunction with the chosen selection criteria to afford the appropriate emphasis to the criteria which reflects their perceived individual importance for the particular project. Scores are then assigned against the criteria for each of the remedial technology or strategy options under consideration thereby enabling ranking of the options according to their global scores.

7.5 Considerations for Management of Remediation Activities

The aspects of a remediation contract involving the ongoing site characterisation and monitoring during remediation activities, the management of mixed wastes, and compliance/validation surveys and assessment are dealt with in previous sections, in particular Section 5.8. The management of mixed low level radioactive wastes is also dealt with in the BNFL Conditions for Acceptance for BNFL Drigg, as combinations of various elements, both radiotoxic and otherwise, can result in difficulties in disposing of such wastes.

The performance of a remediation contract will require various issues, for example site preparation requirements and Health Physics monitoring, to be addressed. Activities which may require planning as part of the civil engineering aspects of a contract include:

- Requirements for on site services during the exercise, for example 'utility' services such as water, electricity etc;
- Excavation and management of uncontaminated soil, for example overburden materials which would be re-used on site;
- Nuisances to neighbouring receptors;
- Management of final restoration.

Part of the overall project planning will involve an appraisal of the likely impact of the works on existing site conditions. In this way, effects on ongoing site operations, inhabitants and so forth can be controlled, and thus, within the Intervention case, a net benefit must be demonstrated.

7.5.1 Health and Safety Management

In addition to standard health and safety requirements issued by the HSE, more specific provision for suitably qualified or trained staff is given in IRR 1985. These regulations require that work with radioactive materials is supervised by suitably qualified Radiation Protection personnel, and so concerns over exposure to site workers during a remediation project may be addressed in this way.

Monitoring by Radiation Protection Supervisors during the remediation works will control exposure of operatives to radioactive materials, and thus also members of the public, as the site will be maintained in a 'safe' condition.

Depending on the scale, duration and nature of the remediation project, it may need to operated under the Construction (Design and Management) Regulations, 1995. Further explanation of these Regulations is given in section 8 below; briefly, they require that various parties to a construction project assume different roles with regard to their health, safety and design responsibilities, ensuring that the works are managed in a "safe" manner. In addition, depending upon specification and operation, remediation plant may be subject to a risk assessment HAZOP process.

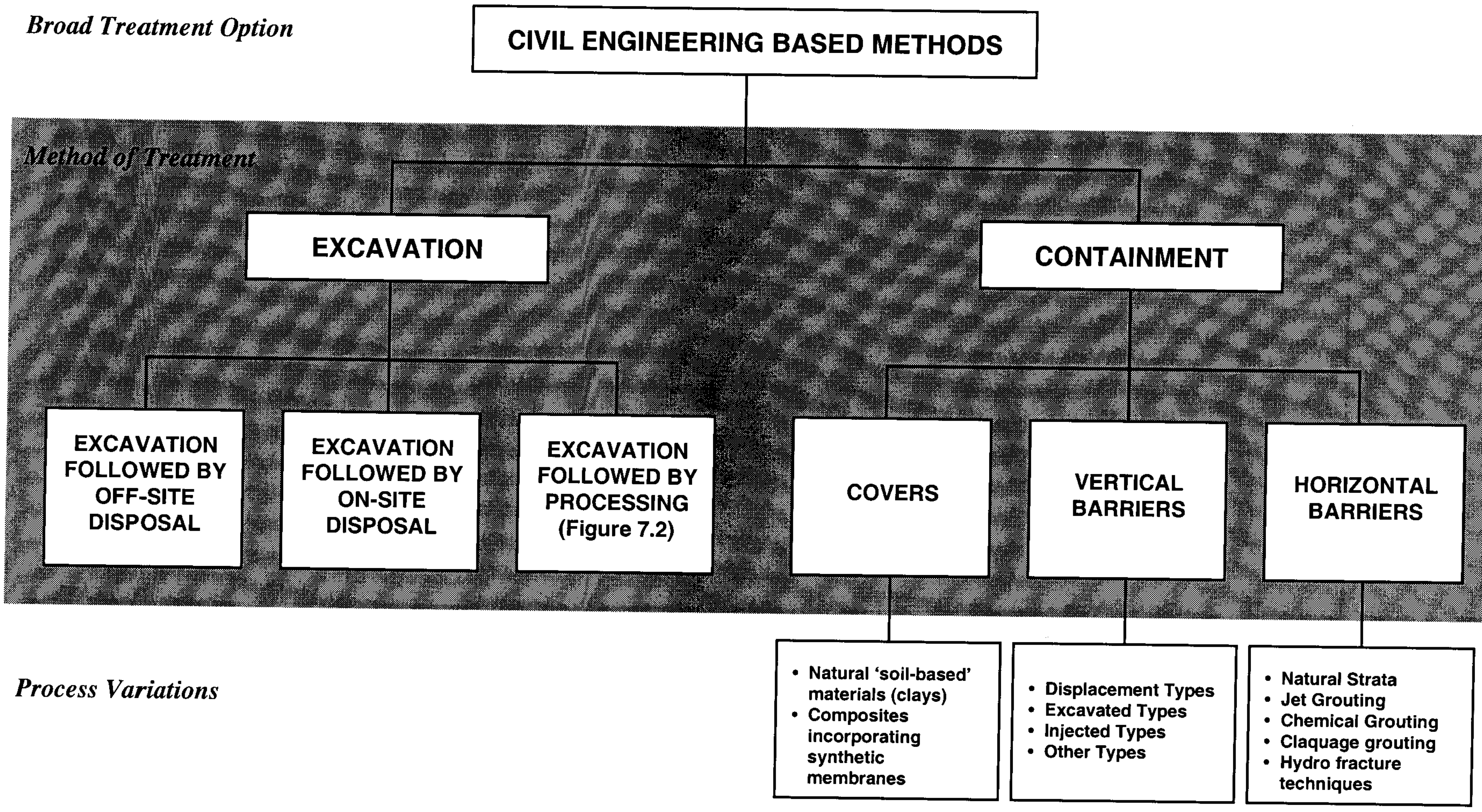


Figure 7.1 Classification Of Civil-engineering Based Remedial Methods

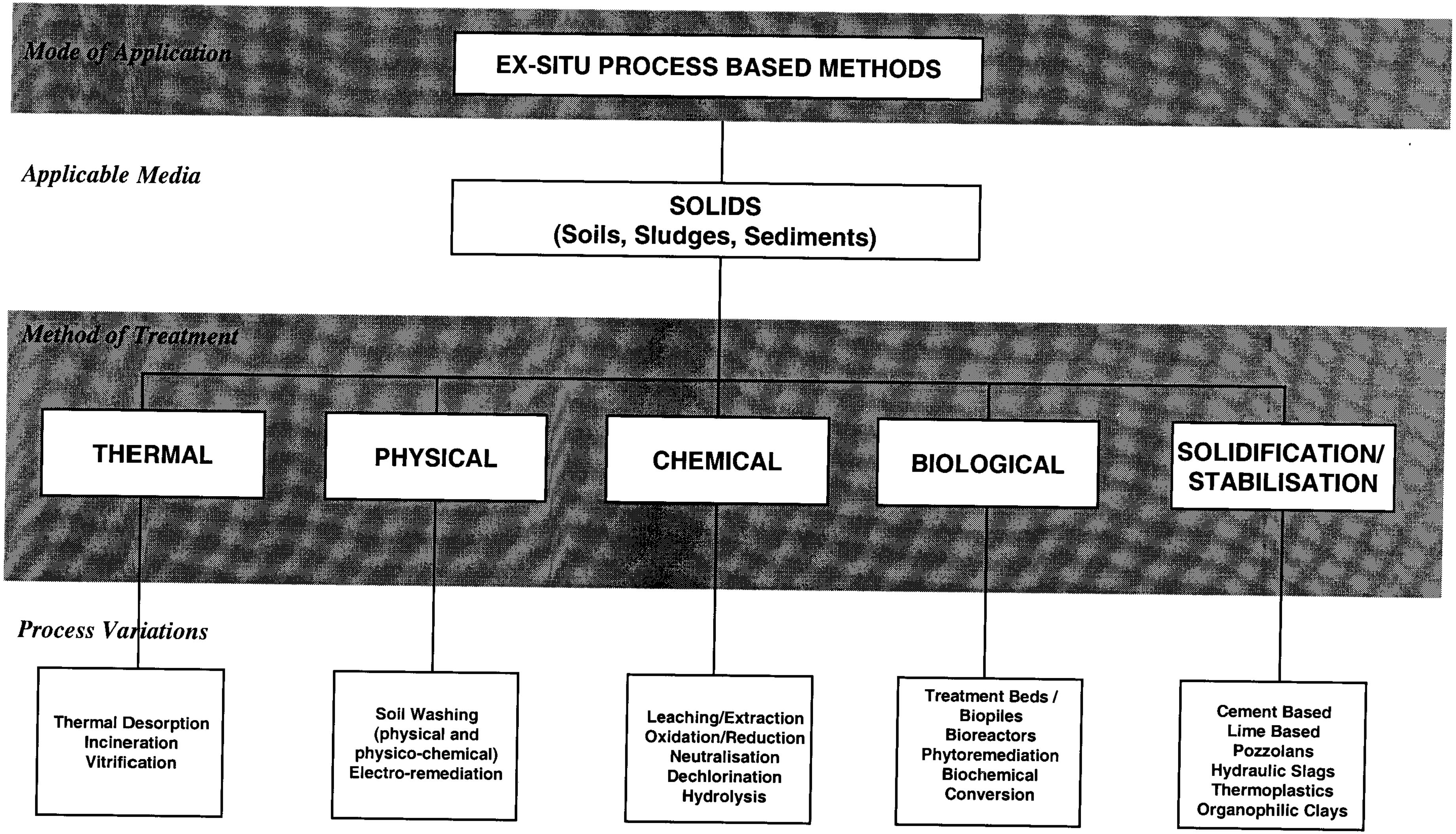


Figure 7.2 Classification Of Ex-situ Process Based Remedial Methods

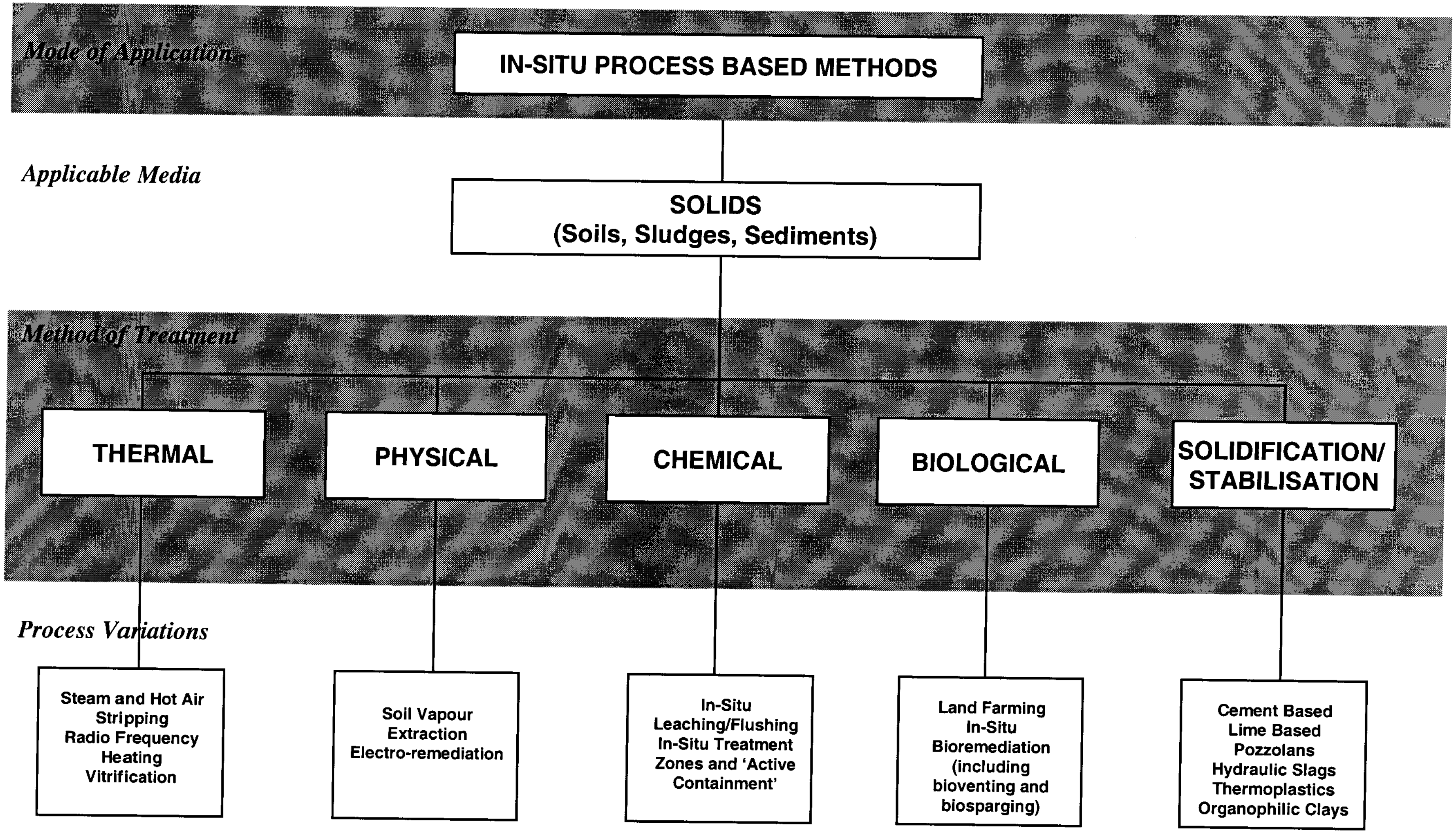


Figure 7.3 Classification Of In-situ Process Based Remedial Methods

8. REGULATORY ISSUES

This section comprises a brief discussion on the implications of the principal legislation and regulatory instruments of relevance to the investigation and remediation of radioactively contaminated land. Where appropriate it points out inconsistencies that may need to be addressed as part of any new regulatory regime.

i) The Radioactive Substances Act 1993 and Subordinate Exemption Orders

ii) The Ionising Radiation Regulations, 1983

iii) Radioactive Materials (Road Transport) (Great Britain) Regulations, 1996

iv) The Construction (Design and Management) Regulations, 1993

v) The Environment and Protection Act 1990 and the Environment Act 1995

vi) Pollution Prevention Control Act, 1999.

8.1 The Radioactive Substances Act; 1993, and Subordinate Exemption Orders

The Radioactive Substances Act, 1993, (RSA'93) the principal legislation governing the keeping, use and disposal of radioactive materials. The Act is currently under consultation for revision, to meet the requirements of the Basic Safety Standards Euratom Directive, 96/29 (DETR, 1999). Of relevance to radioactively contaminated land the Act requires the keeping and use of radioactive materials to be registered and the disposal of radioactive wastes to be subject to authorisation. It also sets out lower limits of activity for naturally occurring radioelements, below which they are not considered to be "radioactive" within the meaning of the Act.

Currently, it is common UK practice that the concentrations defined by RSA '93 are applied as a remediation standard across a radioactively contaminated site when preparing for a change of land use. These definitions, whilst conservative, are not risk based and it is possible that under conservative exposure scenarios that concentrations less than these definitions could pose risks. Although the Act provides a clear numeric definition of what is considered to be radioactive material, its interpretation leads to certain anomalies which impact on the remediation of radioactively contaminated land. For example, the Phosphatic Substances Exemption Order states a schedule of elements, including radium and polonium, that are exempted up to concentrations of 14.8 Bq/g per element. Common practice is to assume radium-226 is in secular equilibrium with its daughter products and therefore with three polonium isotopes. On this basis, the exemption for radium concentrations is reduced by a factor of three and a limit of 4.9 Bq/g is applied. However, natural uranium concentrations are defined as being radioactive at concentrations greater than 11.1 Bq/g and no consideration is given to uranium daughters although the radium-226 decay chain forms part of its progeny. Within RSA '93, the relative radiotoxicity or half life of isotopes would not seem to be the sole consideration; isotopes such as radium-226 are subject to relatively relaxed exemption orders, whereas isotopes such as cobalt-60, with a comparatively low radiotoxicity and short half-life, are not.

It is intended that the proposed radioactively contaminated land regulatory regime will provide risk based assessment levels. There are obvious benefits in this approach in consistency with the risk based procedures for assessing chemically contaminated waste. However, one drawback is that it could potentially lead to a confusing range of definitions of what is "radioactive land" and therefore will need to be accompanied with very clear interpretation guidelines. The proposed regulations could introduce the possibilities of a site being subject to the presence of radioactive materials by reference to the numerical criteria under RSA93, yet not being classified as radioactively contaminated land and vice versa.

8.2 The Ionising Radiation Regulations; 1985

The Ionising Radiation Regulations, 1985 (IRR'85), made under Health and Safety provision, control the workplace exposure of workers to radioactive substances. The regulations provide a different definition of radioactivity to that in RSA '93 and define a "radioactive substance" as a substance with an activity exceeding 100 Bq g^{-1}. It also includes the short-lived daughters of radon-222 as polonium-218, lead-214, bismuth-214 and polonium-214. The legislation defines "work with ionising radiation" as involving production, processing, handling, use, holding, storage, moving, transport or disposal of any radioactive substance, operation or use of a radiation generator, or atmospheric exposure to radon-222 daughters exceeding 6.24 10^{-7} Joules m^{-3}. This legislation may be relevant to the remediation situation where radioactive materials are being routinely handled by site staff, and will have a bearing on the permissible activities and exposures.

Although the Ionising Radiations Regulations 1985 are currently under review, they remain the tool which defines standards of radiological protection within the U.K. They apply to all non-routine as well as routine work involving exposure to radiation.

8.3 Radioactive Material (Road Transport) (Great Britain) Regulations; 1996

The Radioactive Material (Road Transport) (Great Britain) Regulations 1996 (SI No 1350) are the principal legislative tool applied to the transport of radioactively contaminated soils and other radioactive materials that might be disposed of from a contaminated site.

The regulations require that whenever radioactive materials are being transported they must be kept in a suitable receptacle with suitable labelling. In this case 'suitable' means conforming to the packaging and labelling requirements of the International Atomic Energy Agency (IAEA Safety Series 6, 1985) Radioactive materials must be accompanied by information in writing describing the radioactive substance, a statement confirming that it is packaged and labelled in accordance with IAEA requirements and any other information to enable the safe handling of the material.

In the UK the transport of radioactive material is further governed by the following legislation.

Road

The Radioactive Substances (Carriage by Road) Regulations (Northern Ireland) 1983 (SR 1983 No 344). The Radioactive Substances (Carriage by Road) (Amendment) Regulations (Northern Ireland) 1986 (SR 1986 No 61).

Sea
The Merchant Shipping (Dangerous Goods and Marine Pollutants) Regulations 1997 (SI 1997 No 2367). Merchant Shipping Notice No M 1620, "The Carriage of Dangerous Goods and Marine Pollutants in Packaged Form on Ships".

Air
The Air Navigation (No 2) Order 1995 SI No 1970. The Air Navigation (Dangerous Goods) Regulations 1994 SI No 3187 and Amendments 1996 SI No 3100 and 1998 SI No 2536.

Ports
The Dangerous Substances in Harbour Areas Regulations 1987 (SI 1987 No 37).

Rail
The Packaging, Labelling and Carriage of Radioactive Material by Rail Regulations (RAMRail) 1996 (SI 1996 No 2090): Approved Requirements for the packaging, labelling and carriage of radioactive material by rail 1996 edition. The Carriage of Dangerous Goods (Classification, Packaging and Labelling) and Use of Transportable Pressure Receptacles Regulations (CDGCPL) 1996 (SI 1996 No 2092). The Packaging, Labelling and Carriage of Radioactive Material by Rail Regulations (Northern Ireland) (RAMRailNI) 1998 (SR 1998 No 132).

Source: Hansard (1999).

8.4 The Construction (Design and Management) Regulations, 1994

These Regulations, which came into force on 31 March 1995, require companies to consider, and give justification for, Health, Safety and Environmental (HS&E) issues throughout the complete lifecycle of a project. In the context of this study, the Regulations require that due consideration is given to the HS&E issues arising from the decommissioning, demolition, site investigation or other works associated with the redevelopment of sites. The CDM Regulations apportion roles to various parties involved in a project, and require specific tasks to be the preserve of each particular party. A brief summary of the duties of those carrying out the roles is given below.

The **client** has to appoint a planning supervisor and principal contractor. The client must ensure (so far as is reasonably practical) that the construction phase of the project does not start unless a health and safety plan has been prepared in accordance with the requirements of the Regulations. The client can appoint an agent who will be treated for the purposes of the Regulations as the client.

The **planning supervisor** has to ensure that a health and safety plan is prepared, monitor the health and safety aspects of the design, be in a position to give adequate advice to the client and any contractor. They must also ensure a health and safety file is prepared and maintained in respect of the project.

The **designer** is required to make a client aware of the duties under the Regulations to be performed by the client. The designer is also required to ensure that the design avoids unnecessary risks to health and safety or reduces the risks so that the project can be constructed and maintained safely.

The **principal contractor** is required to take over and develop the health and safety plan, co-ordinate the activities of other contractors, in addition to the duties in relation to providing information, training and consultation with employees, including the self-employed.

Other contractors are required to co-operate with the principal contractor. This includes complying with directions given by the principal contractor and providing him with details on the management and prevention of health and safety risks created by the contractor's work on site.

The Regulations apply to all projects that involve construction work, although exclude projects which:

- have a construction phase of less than 30 days; or
- involve less than 500 person-days of construction work; or
- where fewer than five people will be carrying out construction work at any one time.

However, regardless of this exemption, the Regulations apply to **designers** in respect of their obligations within that role, and to demolition/dismantling work regardless of the size of the project. (Winter and Harrison, 1995; Health and Safety Commission, 1995).

8.5 The Environmental Protection Act 1990 and the Environment Act 1995

The Environmental Protection Act 1990 was an innovative piece of legislation aimed at completely re-shaping the approach to environmental protection in England and Wales (it does not extend to Northern Ireland). The key features of the Act of relevance are two fold:

- Part I of the Act introduced a two tier system of pollution control comprising integrated pollution control (IPC) and the local authority air pollution control (LAAPC). IPC recognises that the environment should be considered as a whole and that air, land and water are interfaced. It therefore aimed to provide a "one stop" authorisation procedure for the control of emissions to air, water discharges and hazardous wastes for the major polluting industries. Prescribed processes and substances that are subject to regulatory control are defined in the Environmental Protection (Prescribed Processes and Substances) Regulation 1991. The administrative procedures for authorisation are defined in the Environmental Protection (Application, Appeals and Registers) Regulation 1991.
- Part II of the Act establishes a statutory duty of care on procedures, importers, holders, carriers and persons who treat waste to ensure that:
    - i) it is not illegally managed
    - ii) does not escape from control
    - iii) is transferred only to an authorised person
    - iv) is adequately described and clearly labelled to enable proper handling and treatment.

The Act imposes strict liability for damage caused by waste deposited on land.

The Act also establishes licensing requirements for waste management and treatment facilities.

The Environment Act 1995 established the Environment Agency as the prime regulatory body incorporating the function of the former Local Waste Regulations Authorities, Her Majesty's Inspectorate of Pollution (HMIP), the National Rivers Authority and some function of the Department of the Environment.

Part IIA of the Environmental Protection Act 1990 (inserted by Section 57 of the Environment Act 1995) introduces a new regime of the identification and remediation of land which poses unacceptable risks to human health and the environment.

These provisions do not apply to radioactively contaminated land which remains subject to control under the Radioactive Substances Act 1993 and the Ionising Radiation Regulations as either an industrial control or environmental health issue. However, the Act does provide the Secretary of State with powers to make regulations applying the provision of Part IIA to radioactive contamination with such modification as he considers appropriate. With this in mind the DETR published a consultation paper inviting views on the broad principles and structure of such a regime in February 1998.

8.6 Pollution Prevention Control Act 1999

Enabling regulations for this legislation are currently in draft contained within a recent 4th consultation document on implementation of the IPPC Directive (96/61EC). At this stage it would appear that, although the Act would impact on specified chemically contaminated sites, radioactive substances would appear to be excepted from the definition of a substance.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Radioactive Contaminated Sites in the UK

The report has identified the historical industrial operations and uses of radioisotopes that could have resulted in land contamination. A methodology to assist regulatory authorities in identifying potential contaminated sites has been proposed. It is recommended that this methodology is tested in a pilot region/area where a range of contaminated situation might be expected prior to application of the methodology throughout the UK. As part of the pilot exercise it would be beneficial, following initial site identification, to undertake a select number of site-specific desk studies and screening surveys to better understand the nature of contaminant distribution that might occur on such sites, in order that the extent and likely occurrence of intervention situations arising from the implementation of the proposed regime can be assessed.

9.2 Characterisation Techniques

The range of monitoring technologies and analytical methodologies that may be used in the identification, characterisation and remediation of radioactively contaminated land have been assessed and their applicability and limitation for the more common radioisotopes have been reviewed. To further assist regulatory authorities and other organisations in selecting the right characterisation technique for any situation it would be beneficial to prepare 'technology application sheets' that in a simple format identify the application, suitability for various radioisotopes, limitations, detection limits and cost of commercially available instrumentation/techniques.

9.3 Radiological Assessment of Contaminated Land

An NRPB risk assessment model has been used to develop screening levels that could be used to assist in identifying the need for intervention. The model used has been compared to that used to derive the guideline values for chemically contaminated land (CLEA). Whilst very similar in concept there are some important differences in exposure scenarios and parameter values between the two models. Since it is desirable that there is as much consistency as possible between the radioactive and chemically contaminated regimes it is recommended that further work is undertaken to examine the impact upon screening levels of using, wherever possible, consistent parameters.

A two tier methodology for assessing land is proposed. Firstly, an initial screening assessment is undertaken. Screening values have been devised for two situations; uniform and buried or 'patchy' contamination and for two dose levels 10 mSv/yr and 0.3 mSv/yr. It is suggested that for dose levels above 10 mSv/yr intervention is always necessary and for levels below 0.3 mSv/yr intervention will be rarely justifiable. For sites giving rise to dose levels between these values a second stage site specific risk assessment including a detailed radiological assessment of dose levels will be necessary to determine the need for intervention.

It is recommended that the finalised risk model is tested on some existing well characterised sites to assess its performance in identifying the need for intervention. Since on many sites contamination is in the form of discrete point sources it is desirable to determine that its performance in these circumstances is acceptable.

9.4 Remediation in the UK

The report has considered remediation technologies available for radioactively contaminated land but has particularly focused on application and remediation experience in the UK. To date simple, robust techniques involving identification, segregation, excavation and off site disposal or capping have been most commonly applied. Experience is most widespread in the remediation of sites contaminated with radium-226, thorium-232, caesium-137 and uranium. There is some limited UK based experience in soil washing, phytoremediation and vitrification. It is considered that excavation and disposal is likely to remain the technique of choice, however, more detailed review of the application of emerging technologies being used in the USA on large scale contaminated site problems may be beneficial.

An important concern in the UK is the availability of disposal routes for low level wastes. The principal facility, BNFL Drigg, is a finite and valuable resource and difficulties are already being experienced in the disposal of some wastes. Landfill sites are currently used for exempt wastes, very low level wastes and, in a limited number of cases, for Special Precautions Burial. It may be necessary to consider the greater use of landfills for wastes which represent a low radiological hazard. The implication of this for site licensing, and the safe handling of wastes at sites that may not be designated as radioactive waste but nevertheless contain discrete radioactive sources may need consideration.

Clearer regulatory guidance is needed on what is an acceptable ‘averaging volume’ for consigning wastes for landfill disposal. This is particularly important where contamination is discrete point sources or ‘patchy’ in nature. There is a balance between the increased costs and risk to operatives of segregation with creation of low level wastes for disposal to Drigg versus larger averaging volumes and disposal to landfill that should be assessed.

9.5 Regulatory Issues

If a risk based approach to identifying the need for intervention is adopted then situations may arise where sites will be classified as not being radioactively contaminated when, under the definition of RSA93, radioactive materials may still be present. The implications of this on public confidence, site user acceptance and future purchaser confidence on sale of the site need to be considered.

Also whilst intervention may not be necessary for current site uses it may become necessary if a change of use increases the likelihood of exposure e.g. redevelopment. This is in line with the Governments commitment to the ‘suitable for use’ approach to the control of chemically contaminated land. New land use being considered under planning control systems.

9.6 Implementation

In order to successfully implement the proposed regulatory regime training and dissemination of knowledge to the relevant authorities and responsible staff will be necessary.

The information in this report combined with other source material and recommended supplementary work will provide a basis for developing suitable training material which might include:

- Lectures/seminars
- Training packs
- CD Rom
- Internet site.

Areas/issues which should be covered in any training programme include:

i) Methodologies and techniques for the identification and preliminary assessment of potentially contaminated sites.

ii) Investigation and characterisation techniques to identify contaminating radioisotopes and to quantify the radiological hazard.

iii) Remediation methodologies to reduce the radiological hazard to an acceptable and validation methodologies to demonstrate the acceptability of any residual hazard.

iv) Regulatory definitions and guidelines.

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GLOSSARY

Absorbed Dose	The radioactive energy absorbed per unit mass, measured in grays (Gy – units of joules per kilogram).
Activity	The rate of radioactive decay. Measured in Becquerels.
Activity concentration	The activity per unit mass of a material, measured as the number of Becquerels per gramme, or Bqg^{-1}.
Air sparging	The injection of air into a contaminated medium to strip off contamination.
Alpha	Alpha radiation comprises a helium nucleus (two protons and two neutrons).
Anthropogenic	Man made.
Averaging Volume	The volume over which the activity concentration is measured and averaged to give an average activity concentration for material sentencing purposes.
Background	(Radiation) attributable to number of spatially varying factors, such as underlying geology, which constitutes a "background" level of radiation over a site, against which additional radiation due to artificially present sources can be compared.
Becquerel	One radioactive decay per second.
Beta	Beta radiation comprises an electron.
Bioremediation	The remediation of contamination using biological methods, usually through natural degradation by enhanced populations of bacteria.
Change of use	A situation where a site is redeveloped to a different land use than that previously. Planning permission is required for changes of use out with certain land use classes, elaborated further in Section 6.
Characterisation	The process by which the nature, extent, location and severity of contamination on a site is assessed.
CLEA	Contaminated Land Exposure Assessment Model.
Cosmic Radiation	Radiation from space, predominantly from the sun.
Decay chain	A sequence of radioisotopes which decay from a "parent" to a "daughter" through radioactive emission, ending with a stable isotope. Examples include the uranium and thorium chains.

Detector-based segregation	Segregation and sentencing of radioactive material using an appropriate detection technique, such as sodium iodide scintillation counting.
Deterministic	Observable harm resulting to tissues and organs of the body with increasing levels of ionisation, with the probability and severity of harm increasing statistically with the dose.
Dose	Can be defined as several different quantities. "dose" is the term given to the quantity of radioactive energy absorbed, through whatever means, into the target individual or population. It is usually presented in Grays or Sieverts per annum.
Effective Dose	Measured in joules per kilogram, given the unit Sieverts. The effective dose provides further weighting to account for the varying susceptibility of tissues to damage.
Equivalent Dose	The absorbed dose averaged over the tissue or organ, weighted with an appropriate radiation weighting factor with units of sieverts (Sv), also in joules per kilogram. This is to account for the varying types and energies of the incident radiation, which have been found to affect the probability of stochastic effects.
Exemption Orders	Subsidiary legislation operating under the Radioactive Substances Act, 1993, "exempting" certain radioactive materials and forms up to prescriptive activity concentrations.
Expected Daily Intake	A parameter within the CLEA methodology, representing the endpoint of the process.
Gamma	Gamma radiation is the release of nuclear packing energy, which is electromagnetic in nature and behaves as a photon.
Harm	Injurious effect, qualified in EPA 1990 with "significant", where this is defined.
Hazard Assessment	Phase 1B Risk Assessment: consideration of the plausibility of pollutant linkages and determination of the potential health and environmental risk.
Hazard Identification	Phase 1A Risk Assessment: the identification of the contaminant sources, pathways and receptors, or the pollutant linkage, taking into account the actual or intended use of the site and its environmental setting.
ICRP	International Commission on Radiological Protection

Intervention	An operation where the overall radiation exposure is reduced by influencing the existing situation; by removing existing sources, modifying pathways, or reducing the number of exposed individuals. Intervention should be justified and optimised.
Kerma	The measure of energy transfer from indirectly ionising particles to charged secondaries in an irradiated medium.
Landfarming	The application of contaminated media to land, to allow natural attenuation, bioremediation and possibly phytoremediation to occur.
Luminising	The practice by which instruments, particularly aircraft instruments, were rendered visible in poor light conditions through the application of paint containing radium-226, used for its luminous properties.
Natural Attenuation	The reduction of concentration and degradation of contaminants through natural processes.
No Danger	The release criteria for licensed Nuclear Installations under the Nuclear Installations Act 1965, where a precondition of de-licensing is that there is "no danger" from radioactivity.
Pathway	A pathway, such as groundwater, ingestion, direct exposure, for the pollutant to move along, in the context of the pollutant linkage.
Pica	Also known as geophagia. The deliberate ingestion of soil by young children.
"Polluter Pays"	The principle by which "(the person) … "who caused or knowingly permitted the contaminating substance to be on, in or under the land" is made liable for remediation costs.
Practice	An operations which adds radiation exposures through the addition of new sources, pathways and individuals or the modification of same. Practices require justification, optimisation and the application of individual dose and risk limits.
Phytoremediation	Remediation of contamination using plants, including trees, to remove or "fix" contamination within the biomass.
Radiation	Matter or energy ejected during internal rearrangements of radioactive atoms.
Radioactive Material	At the present time, several definitions exist for "radioactive material", within the Radioactive Substances Act 1993, the Ionising Radiations Regulations 1985 and the Radioactive Materials (Road Transport) Regulations, 1996.

Radioelement	Different radioactive isotopes of the same element, such as uranium-234, 235 and 238.
Radioisotope	Specific term for a radioactive isotope, such as radium-226.
Radiography	The use of radioisotopes to enable the non-destructive internal imaging of either biological matter or industrial products.
Radionuclide	Radioactive materials with the same atomic number, such as lead-214, bismuth-214 and polonium-214, or radium-228, actinium-228 and thorium-228.
Radiotherapy	The use of radioactive emissions in medical treatment.
Receptor	The "target" which is affected by the pollutant. This includes human beings, other living organisms, controlled waters (including groundwater beneath the site), physical systems and built structures which could be affected by the hazard.
Remediation	Any action performed to deal with an environmental problem.
Risk	A combination of the probability, or frequency, of occurrence of a defined hazard (for example, exposure to a property of a substance with the potential to cause harm); and the magnitude (including the seriousness) of the consequences to a specified receptor.
Risk Assessment	An approach by which all pertinent features of the site and surrounding area, for example the geology, hydrogeology, site and proximal land uses and activities, past studies on the site are interpreted in one of three ways; qualitative, semi-quantitative and quantitative.
Risk Estimation	Phase 2 Risk Assessment: estimation of risk (s) that identified receptor (s) will suffer adverse effects if they come into contact with, or are otherwise affected by, contaminant sources under defined conditions.
Risk Evaluation	Phase 2 Risk Assessment: evaluation of the need for risk management action (i.e. risk reduction or control measures) having regard to the nature and scale of risk estimates, any uncertainties associated with the assessment process, and, where further action is required, the objectives, broad costs and benefits of that action.
Schedule One	A Schedule within RSA 1993 that defines solid, liquid and gas/vapour activity concentrations for actinium, lead, polonium, protoactinium, radium, radon, thorium and uranium at which these substances are considered "radioactive".
Source	A source of pollution (the hazard), in the context of the pollutant linkage.

Stochastic	A stochastic effect is the reproduction of a modified viable cell, which may result in the manifestation of a malignant condition, or cancer, the severity of which is not altered by the intensity of the original dose.
Teletherapy	See Radiotherapy.
Use Classes Order	Regulatory system for controlling the use and redevelopment of land. Defines a number of categories for land uses, from A to D, with subdivisions within each class. Planning permission is often required for changes of use between categories. Elaborated further in Section 6.
Vitrification	Transformation of contaminated soils into a vitrified glass resistant to weathering, through the application of a voltage.
Validation	The process which occurs as a final stage in a remediation project, and which allows the detection of any remnant activities and volumes remaining after the remediation exercise has been carried out. Validation must be scoped to provide confidence to all stakeholders in the quality of the remediation.
Windrow	A stockpile of material shaped in such a manner to allow the efficient progression of bioremediation.
X-Rays	X-Rays are produced when an electron is stopped in material, and can also be produced when an incoming electron has sufficient energy to displace an inner orbit electron. Outer orbit electrons are attracted, and X-Rays are the emission of the difference in orbital energies.

Appendix A
Extract from Environment Agency Specification - HOCO 323

4 Pages

iii) To provide recommendations for the guidance material to be issued by the statutory bodies and the content of guidance material and training to be used by regulators.

Any work required for the development of techniques listed in (i) above, or for the production of guidance or training material to be used by the regulators will not be the subject of this contract.

4. PROJECT-PLAN

4.1 OVERALL APROACH

A number or radioactively contaminated land sites have been investigated and remediated in recent years. The project is primarily intended to be an review of experiences gained in this work and the collation of information tin relevant techniques for site characterisation, assessment of risks and remediation and the elucidation of criteria. The project will also indicate how this information can be provided to the statutory bodies and Agency inspectors in a useful form.

4.2 TASKS

The contractor will carry out the tasks set out below.

Task 1 The contractor shall carry out a brief review of the range of radioactively contaminated land sites likely to be encountered in the United Kingdom. This is to take into account the various types of historical activities which may have resulted in radioactively contaminated land. This is for the purposes of framing the techniques to be addressed under this contract and shall identify characteristics of processes which are relevant to the work to be carried out under this contract.

Task 2 The contractor shall provide a short review of radioactively contaminated sites that have been remediated in the United Kingdom, indicating the nature of contamination and how investigation and remediation was achieved.

Task 3 The contractor shall review the possible criteria needed to judge whether suspect land should be designated as radioactively contaminated and to aid remediation of such designated sites. These criteria may include, but are not necessarily limited to:

- what constitutes an intervention level for contaminated sites in terms of dose or risk;
- the present and likely use (bearing in mind its wider environmental setting) of the site;
- the degree of homogeneity of contaminant concentrations before and after remediation;

- the technical requirements to differentiate concentrations above background and de minimise levels;

- the averaging techniques;

- the availability of disposal sites for selected material removed from the radioactively contaminated site

- the acceptability of residual risks

The contractor shall collate the information collected and present it in a concise but readable form with recommendations for a set of workable criteria.

The contractor shall provide recommendations for the guidance material to be issued by the statutory organisations to the regulators.

Task 4 Based on the output of Tasks 1 and 2, the contractor shall review the techniques which are applicable to the identification of potentially contaminated sites. Recommendations shall be made by the contractor on the most appropriate techniques to be used. Estimates of resource requirements shall be provided as part of the work.
Task 5 The contractor shall provide a review of site characterisation techniques which may be applied to potentially contaminated sites. The review' shall include, but not be limited to:

- Hand held monitors for ground surveys
- Sampling techniques for analytical purposes
- Aerial gamma surveys using helicopters or small planes

For the techniques described, the contractor shall set out how the techniques would be employed, their applicability, capabilities and limitations, and an indication of cost of using the techniques.

Task 6 The contractor shall provide an evaluation of how doses and risks resulting from contaminated land could be assessed. The contractor shall consider appropriate methodologies and make recommendations for a preferred approach. The assessments of dose and risk will be based on the' survey results, taken together with current and reasonably foreseen activities associated with the site.

In this context it is important to recognise that the following:

- The methodology should be based on the current use of the site. As discussed in the "Background" section to this specification, where new uses of sites are to be proposed and those proposed uses would require an application for planning permission, problems arising from existing contamination would be dealt with under existing planning and building control systems.

- The methodology must be as simple as possible to apply, and must be transparent. The methodology would need to be applied to a wide variety of sites and used and understood by people having a wide range of expertise in radiological assessments.

- It is likely that when sites considered as potentially contaminated are investigated, a large number turn out to have insufficient contamination to be classified as legally "contaminated". A two tier assessment methodology may therefore be appropriate and this should be considered by the contractor. This could, for example, utilise a screening assessment based on derived levels as an initial assessment and more detailed site specific assessments for sites not initially screened out.

- The analysis of doses and/or risks must be fit for the purpose of forming an input to the decisions to be taken on what remediation techniques should be used and what their end points should be.

- The consideration of dose and assessment methodologies shall take into account the expected costs of assessment.

Task 7 The contractor shall provide a review of remediation techniques which may be applicable to radioactively contaminated land sites. The review shall indicate:

- The availability of techniques and the degree to which they represent proven technology.
- The capabilities and limitation of the techniques.
- An indication of costs associated with application of the techniques.
- The options for, and implications of managing radioactive wastes arising from remediation. This is to include consideration of disposal routes and the availability of those routes.
- The relevance of ongoing site characterisation and assessment during remediation e.g. continued monitoring during remediation of contaminated soil.
- Other requirements associated with remediation, namely requirements for services during remediation, excavation of non-active soil, disruption and relocation of inhabitants, the potential for doses to operators and members of the public during remediation and reinstatement of the site to an acceptable condition.

Task 8 Other aspects associated with the regulator's responsibilities. At this stage the Agencies need to understand the totality of the aspects which will apply to it in discharging its responsibilities. The contractor should identify and discuss those aspects which will need to be considered. These may include:

- Implications of the Ionising Radiation Regulations 1985 for Environment Agency/SEPA/DoE (Northern Ireland) staff and contractors involved in characterisation and remediation work.
- Requirements for monitoring during remediation work e.g.. airborne dust monitoring.
- Records and quality assurance.

Task 9 The contractor shall describe any areas requiring resolution in order to finalise guidance to regulators. It is the intention to provide guidance to regulators on:

- the approach to be taken for the identification of potentially contaminated sites.
- techniques to be applied for the characterisation of radioactively contaminated land.
- risk assessment techniques.
- provision of guidance and training to inspectors on securing remediation, to address remediation by responsible persons, drafting remediation notices and specification of remediation by the Agencies.

Guidance on securing such services through external contract by the Agencies need to be addressed. An important aspect is the form of specification and provision of information on contamination and remediation end points to minimise contract costs and cost uncertainties.

4.3 PROJECT MANAGEMENT

The contractor shall agree project milestones with the Project Manager before commencement of work and these set out in the form of a bar chart. Any changes to this shall be agreed with the Project manager, and a new bar chart prepared, with edition numbers, to cover such changes.

The contractor shall arrange for project meetings at six weekly intervals. The frequency of progress meetings may however, be varied by the Environment Agency Project Manager. These meetings will be to discuss contractual issues including overall progress. For this purpose, a short report will be required, to be distributed to all participants one week before the date of the meeting. The core of the report will be in the form of an annotated bar chart indicating progress on the tasks, plus background text where necessary.

Minutes of the quarterly meetings shall be produced by the contractor and distributed to participants within two weeks of the meeting.

Meeting locations will be determined by the contractor in consultation with the Project Manager. However, it is envisaged that a minimum of 50% of the meetings will be held at the Environment Agency's offices in Bristol.

4.4 LIAISON

In the course of the contract, the contractor will need to liaise with the following organisations:

- staff of the Environment Agency, SEPA and the Departmment of the Environment (Northern, Ireland), as required, in undertaking this work;
- DETR and the Welsh and Scottish Offices
- HSE and NPRB.

5. DELIVERABLES

Appendix B
Common Radioisotopes and Decay Chains

6 Pages

Table B1 Common Radioisotopes

Element	Radio – Isotope	Half Life	Emission	Detection Method	Comments
Actinium	Ac-227	21.6 y	Beta	GFPC, BC	
Americium	Am-241	458 y	Alpha	AS	
Caesium	Cs-134				
	Cs-137	30 y	Beta	BC, GS	
Carbon	C-14	5730 y	Beta	GFPC	14N (n,p) 14C,a thermal neutrons from cosmic or nuclear weapon sources reacting with N2
Cerium	Ce-144	284 days	Beta	BC, GS	
Chlorine	Cl-36	3.1E+05 y	Beta	BC, GFPC	
Cobalt	Co-60	5.26 y	Beta	BC, GS	From nonfission neutron reactions in reactors
Curium	Cm-244				
Europium	Eu-152	13.3 y	Beta	GFPC, LS, GMC	
	Eu-154	8.8 y	Beta	GFPC, LS, GMC	
	Eu-155	4.96 y	Beta	GFPC, LS, GMC	
Iodine	I-131	8 days			
Iron	Fe-55				
Krypton	Kr-85	10.76 y	Beta	BC, GFPC	
Lead	Pb-210	22.3 y	Beta	GFPC, BC, GS	226Ra – 6 steps – 210Pb
Manganese	Mn-54	310 y			
Neptunium	Np-237				
Nickel	Ni-63	100 y	Beta	LS, GMC, GFPC	
Plutonium	Pu-238	86 y	Alpha	AS, XRF	
	Pu-239	2.43E+04 y			238U (n,□) 239Pu, neutron capture by Uranium
	Pu-240				
	Pu-241				
Polonium	Po-210				
Potassium	K-40	1.4E+09 y			0.0119% of natural potassium
Promethium	Pm-147	2.62 y	Beta	GFPC, GMC	
Protactinium	Pa-231				

Element	Radio – Isotope	Half Life	Emission	Detection Method	Comments
	Pa-234	6.75 h	Beta	GFPC, BC, GS	
Radium	Ra-226	1602 y	Alpha	GS, AS	
	Ra-228	5.7 y	Beta	BC	
Ruthenium	Ru-106				
Samarium	Sm-147				
	Sm-151	93 y	Beta	GFPC, GMC, LS	
Silicon	S-32	~ 300 years			40Ar (p,x) 32Si, nuclear spallation (splitting of the nucleus) of atmospheric argon by cosmic-ray protons
Strontium	Sr-90	28.1 y	Beta	GFPC, BC	
Technetium	Tc-99				
Thorium	Th-228	1.91 y	Alpha	GFPC, BC	
	Th-229				
	Th-230	8.0E+04 y	Alpha	AS	238U – 3 steps – 230Th produced in-situ
	Th-232	1.4E+10 y	Alpha	AS	
Tritium	H-3	12.3 y	Beta	GFPC	
Uranium	U-233				
	U-234	2.4E+05 y	Alpha	AS, BC, XRF	
	U-235	7.0E+08 y	Alpha	AS, BC, XRF	
	U-236				
	U-238	4.5E+09 y	Alpha	AS, BC, XRF	

After CIRIA (1996) and Manahan (1993).

Key:

GFPC	Gas Flow Proportional Counter
AS	Alpha Spectrometry
LS	Liquid Scintillation Counter
GMC	Geiger-Muller Counter
GS	Gamma Spectroscopy
BC	Beta Counter
XRF	X-Ray Fluorescence

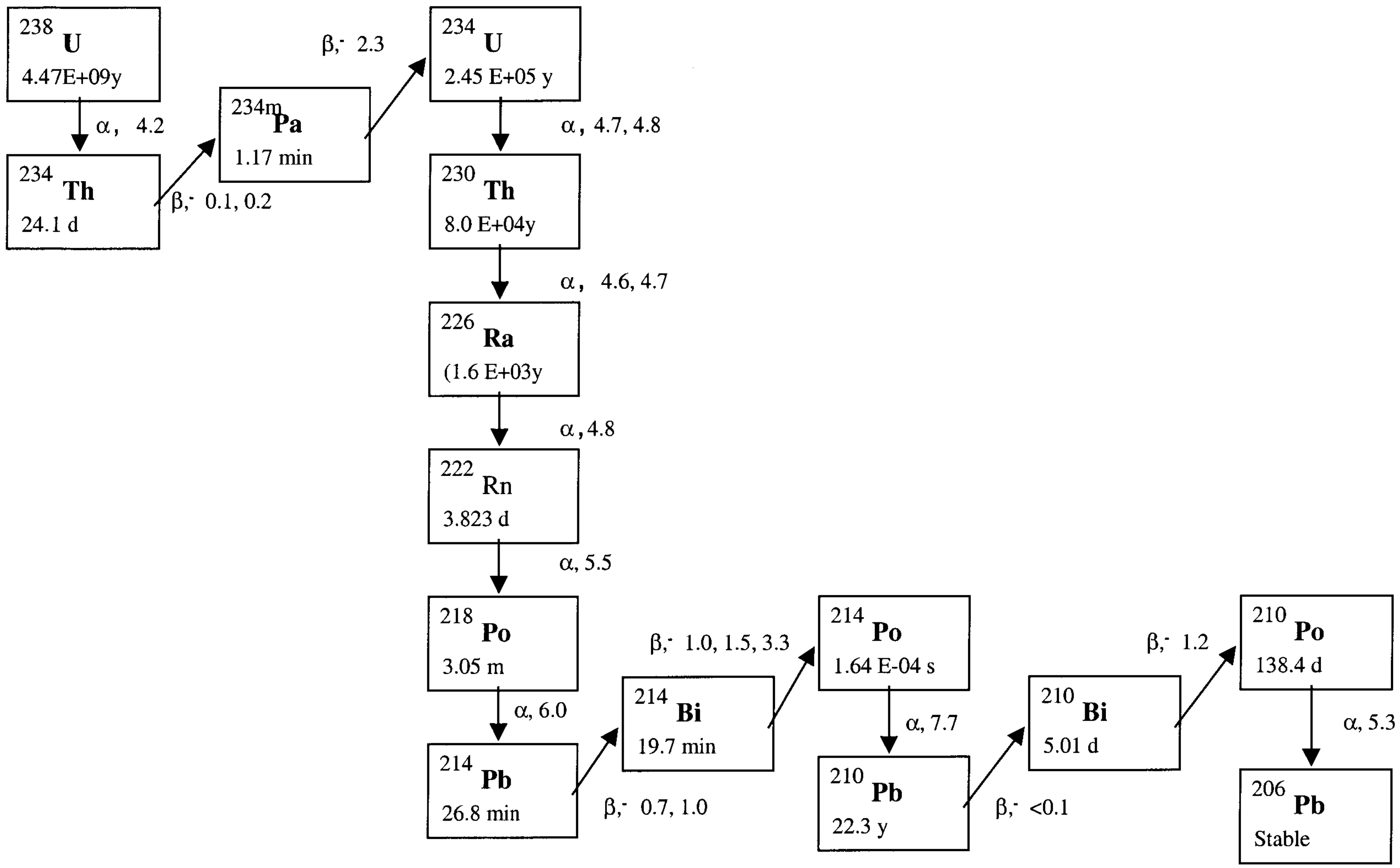

FIGURE B2.1 **THE URANIUM SERIES** (Alpha (α) and Beta (β) energies in MeV)
After Hughes and Shaw, 1996

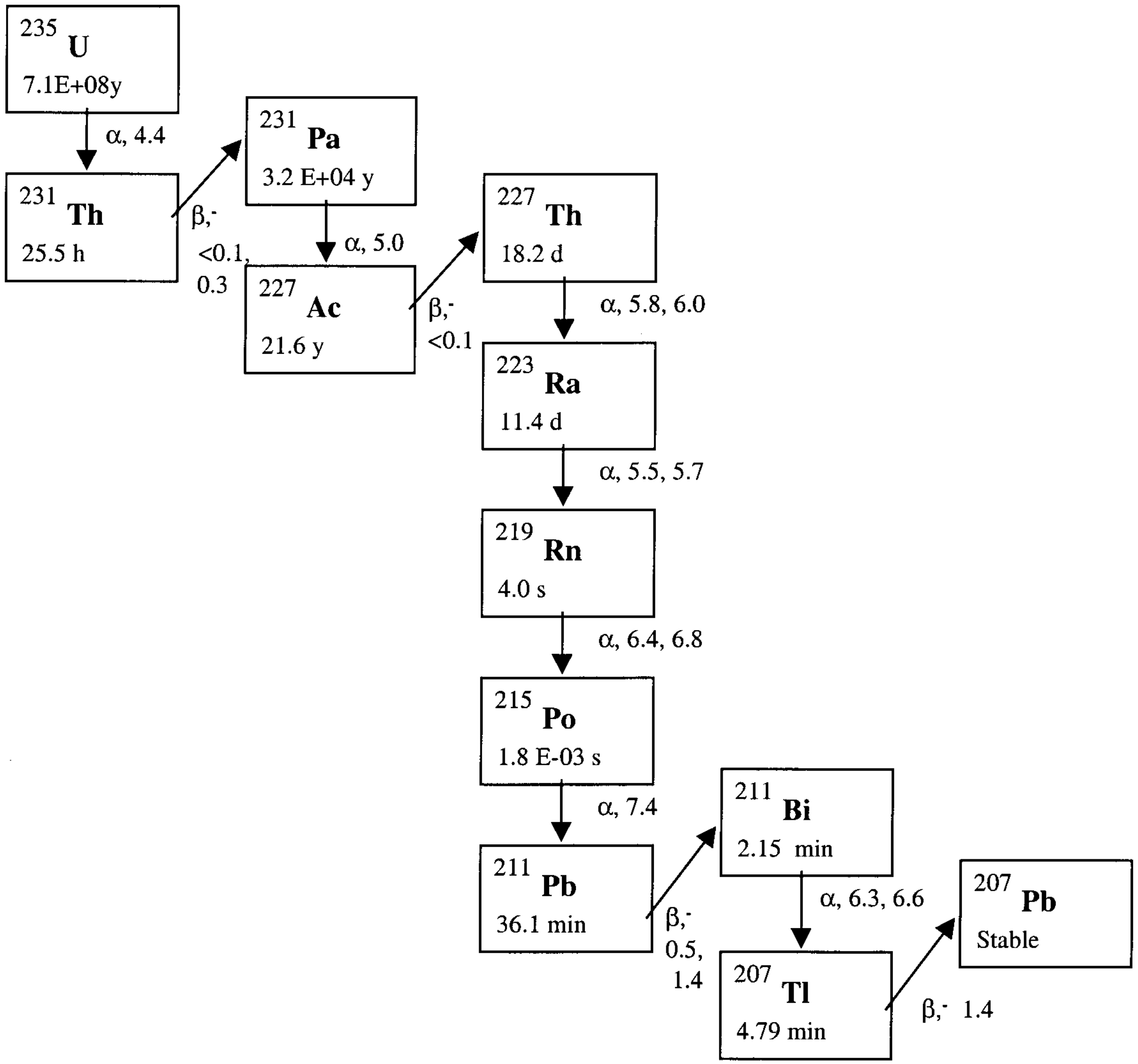

FIGURE B2.2 **THE ACTINIUM SERIES** (Alpha (α) and Beta (β) energies in MeV)
After Hughes and Shaw, 1996

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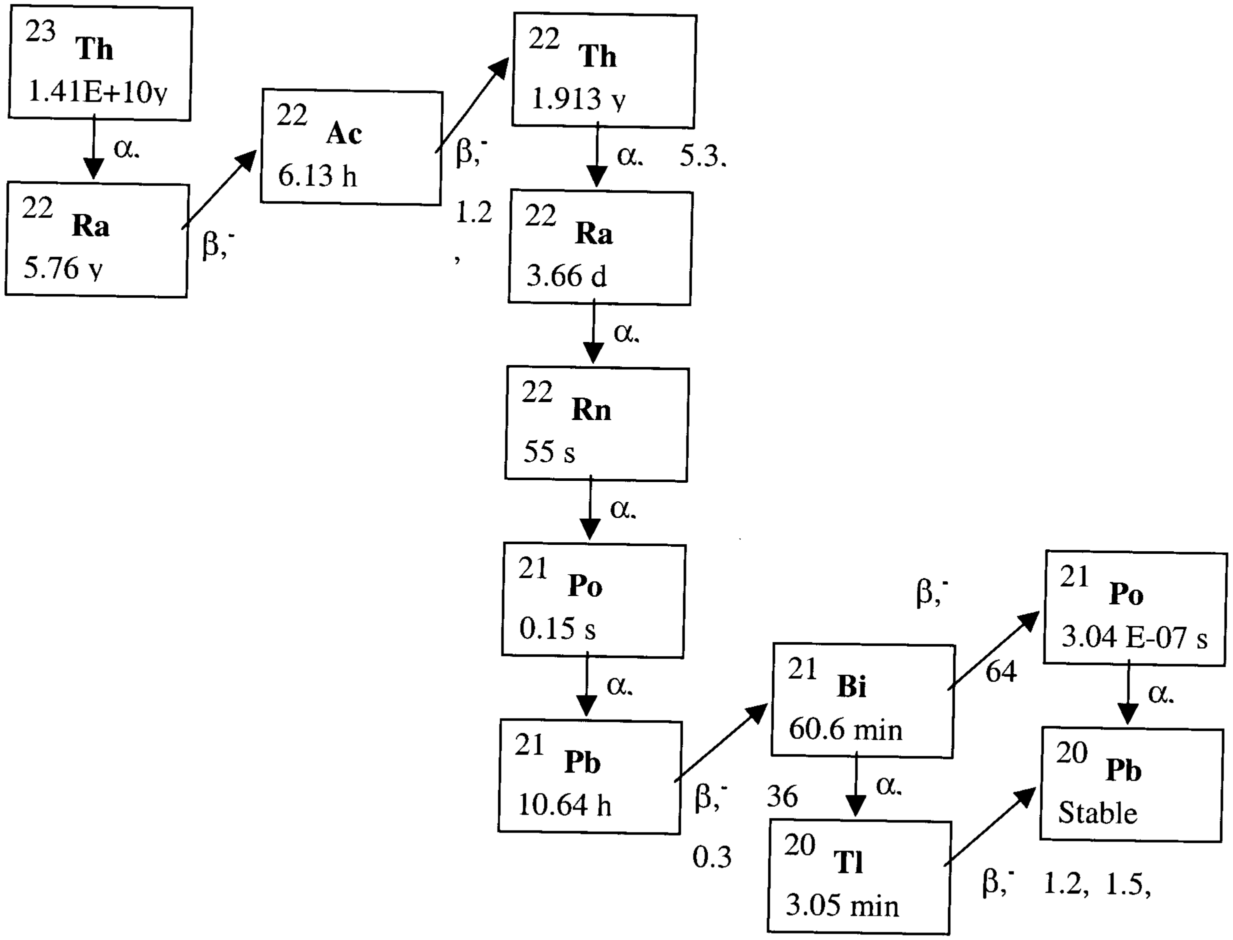
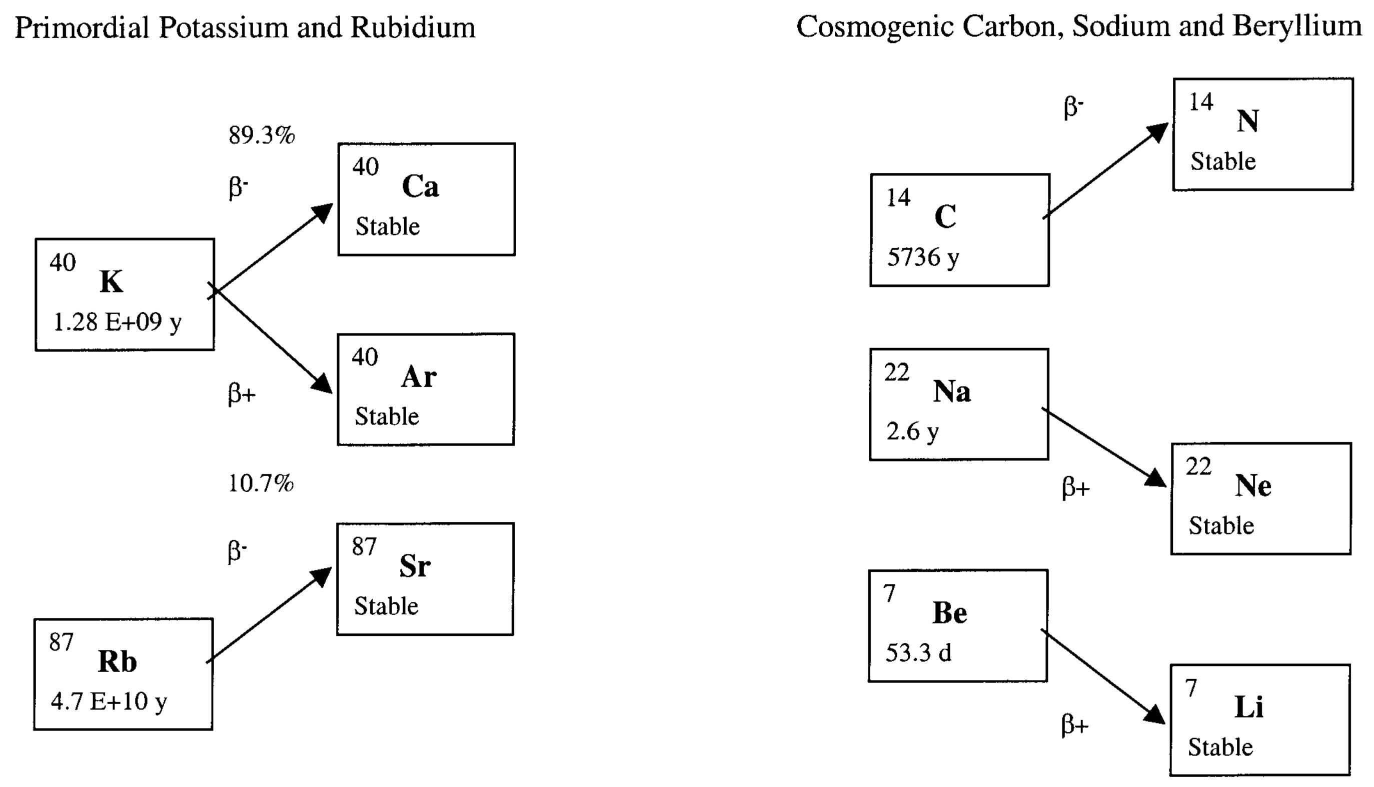


FIGURE B2.3 **THE THORIUM SERIES** (Alpha (α) and Beta (β) energies in MeV)
After Hughes and Shaw,



Primordial Potassium and Rubidium

Cosmogenic Carbon, Sodium and Beryllium

FIGURE B2.4 SOME OTHER NATURAL RADIONUCLIDES
After Hughes and Shaw, 1996

16022W146

Appendix C
Phase One Desk Study: Typical Documentary and Information Sources

4 Pages

Table C1 Typical Documents Inspected as part of a Desk Study

Type of Information	Principal Characteristics	Sources
Principal Mapping		
Ordnance Survey topographical maps. OS Special Maps and books.	Large Scale Maps 1:1250 scale, covering major urban areas of Great Britain, 1:2500 scale from 1853, covering the rest of Great Britain, apart from areas of mountain and moorland, 1:10560 scale (6" to 1 mile) from 1840; cover the whole of Great Britain, but are being replaced with 1:10000 scale maps. Small Scale Maps 1:25000 scale first series excludes the Scottish Highland and Islands – this is being replaced with the second series which covers the whole of Great Britain, 1:50000 scale first and second series, having replaced the 1 inch to 1 mile series, 1:250000 scale, 1:625000 scale; includes specialist maps on route planning, administration, archaeology and geology. British Geological Survey geological maps at 1:50000 or 1:63360 scale in Solid and Drift editions; Soil Survey maps for the Soil Surveys of England and Scotland; Aquifer Vulnerability Maps; Archaeological and historical maps and texts; Professional papers, Gazetteer, place names on maps of Scotland and Wales;	Early maps and editions may be available from The British Library or the Map Rooms of Welsh and Scottish National Libraries. Also from local libraries and the County Record Office, Royal Commissions on Ancient and Historic Monuments in England and Scotland Catalogues available from the Ordnance Survey, Environment Agency.
Supplementary Mapping	Tithe Survey maps (usu. 1:4752 or 1:2736) from 1836 to 1860 for rural and urban areas; also enclosure maps; Plans of public and statutory undertakings; Insurance plans for 46 major towns, 1885-1940, 1:480 scale; Land Use Survey maps; Survey of Contaminated Land, Welsh Office;	County Record Department, MOD Offices; House of Lords Record Office (for plans forming part of Acts of Parliament); Public Record Office; local and national reference libraries; The Coal Authority.
	Admiralty Charts and hydrographic publications.	Hydrographic Office.
Principal Collated Sources		
Site Reconnaissance	Current status and layout of site, acquisition of current photographic records, plans, brief research visit to local sources etc.	Suitable body or individual.

Table C1 (continued) Typical Documents Inspected as part of a Desk Study

Type of Information	Principal Characteristics	Sources
Regulatory Records	Environment Agency/SEPA/NIHS (water resources, development control, RSA/IPC authorisations, waste regulation etc); Local Authority (past waste disposal locations and practices, APC authorisations, planning, drainage); HSE/HAS (NI), NRPB, DOE/DETR, NII, DRPS	Local Area offices.
Meteorological and Hydrological Records.	Weather observations from selected locations in the UK; Surface water runoff data; groundwater level data.	Meteorological Office, Water Utilities, Institute of Hydrology
Photographic Data.	Vertical air photographs (c.1945 onwards); oblique air photographs (various periods); Special Surveys using remote sensing; Ground based photographs.	Central Register of Air Photographs, County planning offices, Ordnance Survey, Commercial companies Local libraries and owners.
Directories.	Local Street Directories (1850 onwards), e.g. Kelley's; Trade and Business Directories.	Local libraries, The British Library, various publishers and trade associations.
Company Records	Drawings, production logs, maintenance and supplier records, environmental audits, COSHH assessments, R&D activities; Archival information, title deeds.	Contacts on the site or former employees.
Supplementary Collated Sources		
Local Studies.	Victoria County History Series; Local histories, newspapers, local society publications and proceedings.	Local and reference libraries, societies and industries.
Technical / Professional	Details of industrial processes, specific descriptions of sites and plants; Site records of owners, occupiers or operators in public and private hands. National Register of Archives.	Local and reference libraries, societies and industries.
Personnel (active site)	Ad-hoc information, site and process plans, anecdotal information, detailed history.	Interviews with Plant, Safety and Production Managers, Employees.
Other Organisations	British Coal, Opencast Executive, British Geological Survey, Water, Gas, Electricity and Telecoms suppliers.	

After BSI (1988), CIRIA (1995 and 1996), DOE (1994c).

Table C2 Information Source Contacts

Name/Source	Contact Details
Association for Industrial Archaeology	The Wharfage, Ironbridge, Telford, TF8 7AW
Association of Independent Museums	Hotties Science and Art Centre, PO Box 68, Chalon Way, St Helens, Merseyside, WA9 1LL.
Aquifer Vulnerability Maps (Policy and Practice for the Protection of Groundwater mapping)	The Publications Centre, PO Box 276, London, SW8 5DT. Tel: 0171 873 0011.
BG (Property Division) plc. (landowner for many former coal carbonisation and other gasworks sites)	BG (Property Division) plc., Aviary Court, Wade Road, Basingstoke, Hampshire, RG24 8GZ. Tel: 01256 308803.
British Archives Council (register of archives only)	The Clove Building, 4 Maguire Street, London, SE1 2NQ.
British Geological Survey (geological maps and borehole records)	British Geological Survey, Keyworth, Nottingham, NG12 5GG. Tel: 0115 936 3100.
Cadw: Welsh Historic Monuments	Crown Building, Cathays Park, Cardiff, CF1 3NQ. Tel: 01222 500200.
Chas E Goad Ltd. (publishers of large scale Fire Insurance Plans for a number of towns)	Chas. E Goad Ltd., 8-12 Salisbury Square, Old Hatfield, Hertfordshire, AL9 5BJ.
County Record Offices	Local Authority for area of site.
Environment Agency/SEPA/NIHS	Local Area offices
Health and Safety Executive (HSE)	Area Offices
Institute of Hydrology	Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX11 8BB. Tel: 01491 38800.
Kelly's Directories Archives Division	IPC Business Press Ltd., Quadrant House, The Quadrant, Sutton, Surrey. Tel: 0181 652 3500.
Land Use Survey	Director of the Land Use Survey, King's College (Strand), London, WC2R 2LS. Tel: 0171 836 5454.
MOD – Defence Estate Organisation	Blakemore Drive, Sutton Coldfield, West Midlands, B75 7RL. Tel: 0121 311 3793.
Ordnance Survey	Ordnance Survey, Romsey Road, Southampton, SO16 4GU. Tel: 01703 792000.
Royal Commission on Ancient and Historic Monuments	Royal Commission on Ancient and Historic Monuments in England, National Monuments Record Centre, Great Western Village, Kemble Drive, Swindon, SN2 2GZ. Tel: 01793 414600. Royal Commission on Ancient and Historic Monuments in Scotland, John Sinclair House, 16 Bernard Terrace, Edinburgh, EH8 9NX. Royal Commission on Ancient and Historic Monuments in Wales, Crown Building, Plas Crug, Aberystwyth, Dyfed, SY23 1NJ. Tel: 01970 621233

Table C2 (continued) **Information Source Contacts**

Name/Source	Contact Details
Soil Surveys	The Soil Survey of England and Wales, Silsoe Campus, Silsoe, Bedfordshire, MK45 4DT. Tel: 01525 860428. The Soil Survey of Scotland, Macaulay Institute of Soil Research, Craigiebuckler, Aberdeen, AB9 2QJ. Tel: 01224 318611.
The British Library	The British Library, Map Room, Great Russell Street, London, WC1B 3DG. Tel: 0171 636 1544
The Coal Authority (Coal Mining Searches)	The Coal Authority, Mining Reports, 200 Lichfield Lane, Mansfield, Nottinghamshire, NG18 4RG. Tel: 0845 762 6848.
The Central Register of Air Photographs	The Central Register of Air Photography, Scottish Development Department, Room 1/21 New St Andrew's House, St James Centre, Edinburgh, EH1 3SZ. Tel: 0131 556 8400. The Central Register of Air Photography, Welsh Office, Room 0-003 Crown Offices, Cathays Park, Cardiff, CF1 3NQ. Tel: 01222 823815
The Meteorological Office	The Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ. Tel: 01344 420242.
The National Library of Scotland	National Library of Scotland, George IV Bridge, Edinburgh, EH1 1EW. Tel: 0131 226 4531.
The National Library of Wales	National Library of Wales, Aberystwyth, Dyfed, SY23 3BU. Tel: 01970 623 816.
The National Register of Archives	Quality House, Quality Court, Chancery Lane, London, WC2A 1HP. Tel: 0171 242 1198
Welsh Archaeological Trusts	C/o The Clywd-Powys Archaeological Trust, 7a Church Street, Welshpool, Powys, SY21 7DL. Tel: 01938 553670.
Welsh Office	The Welsh Office, Crown Offices, Cathays Park, Cardiff, CF1 3NQ.

After DOE (1994c), CIRIA (1996), BSI (1988)

Appendix D
Potentially Applicable Nuclear Effluent Treatment Technologies

5 Pages

Appendix D

Potentially Applicable Radioactively Contaminated Water Treatment Technologies

Classification of the treatment of contaminated land into civil engineering and process based technologies is also potentially applicable to the classification of groundwater treatment technologies. In addition, the familiar division of in-situ and ex-situ techniques is also possible. There are also several in-situ groundwater treatment technologies that have parallels in the contaminated soil treatment range, such as reactive permeable barriers and hydraulic control measures. Consequently, these techniques will be considered within the review that follows.

Much of the "established" track record of groundwater treatment technology is based on hydrocarbon and heavy metal treatment, such as VOC contamination, diesel and aviation fuel spillages, petrol station remediation and so forth. Comparatively little material was found on the radioactive contamination of groundwater, although some techniques were found to be applicable through their application to heavy metal contamination. However, nuclear site operation processes, specifically the treatment prior to discharge or reuse of storage tank liquors, cooling waters and other process waters, could be applicable to contaminated groundwaters, where these are treated on an ex-situ basis. A good general reference source for process treatment of releases to water from nuclear facilities is the Environment Agency's Technical Guidance Note A6 (EA, 1999).

In-Situ Technologies

Several references were located on in-situ treatment of radioactively contaminated groundwater, one of which dealt with a case study. Dwyer and Marozas (1997) studied the in-situ remediation of uranium contaminated groundwater, with special application at the uranium mill tailing remedial action (UMTRA) sites throughout the U.S. An in-situ passive reactive barrier (containing, in the experiment, metallic iron as the reactive material) was positioned to treat the mill tailings effluent. The iron media reduced and/or adsorbed the uranium, and the technique has also been used with selenium, molybdenum and arsenic.

A second reference (PNNL/STCG, 1999) is a statement of technology need/opportunity for the in-situ remediation of strontium-90 in groundwater beneath the 100-NR-2 operable unit, within the Hanford 100-N site in the U.S. This groundwater ultimately discharges to the Colombia River, and is currently being treated with an ex-situ "pump-and-treat" process, which is effectively containing the source while radioactive decay is reducing the inventory of strontium. Calculations on the rate of decay of the strontium have shown that the remediation would have to continue for another 280 years to achieve safe drinking water standards, and so an in-situ technology is sought to reduce the project lifetime and consequent expenditure. The Pacific Rim Enterprise Centre (1999) summarises several technology needs to deal with the strontium-90 problem generated from the 100-N area. These include shallow remediation using phytoremediation and electrokinetics to minimise the transport of contaminant to the Columbia River as unobtrusively as possible, impermeable barriers using electroremediation for shallow remediation and soil flushing for deep remediation, permeable barriers to support deep remediation by soil flushing, deep remediation with chemically enhanced soil flushing or fixation to prevent recontamination, and monitored natural attenuation. This is one of the programmes supported by the U.S. Department of Energy (DOE) Innovative Technology Remediation Demonstration Program (ITRD).

Natural attenuation is often seen as a suitable option for the in-situ remediation of contaminated soils and groundwaters, although the emphasis both in the U.S. and the U.K. on more common natural attenuation cases, such as fuel and hydrocarbon spillages, is on the establishment of the options viability, not its use as a default technique. Waters *et al*, (1998) discusses the various factors which control the performance of natural attenuation of non-active and radioactive metals, including uranium, plutonium, strontium, americium, caesium, iodine, technetium, thorium and cobalt. Principal factors controlling the adsorption/desorption of these radioelements include the pH, alkalinity, redox potential (Eh) and iron hydroxide availability. Natural attenuation for radionuclides may include their adsorption onto a soil matrix for sufficient time that the transit time to receptors is increased so that the resultant hazard is reduced below a certain threshold. Consequently, natural attenuation may be suitable for low concentrations of radioelements where other remediation measures are not justified.

Ex-Situ Technologies

A considerably greater range of technologies could potentially be available for the treatment of radioactively contaminated groundwater, following extraction from the ground using a "pump-and-treat" system. This involves the drilling and installation of extraction boreholes to a depth sufficiently below the groundwater level, and the pumped extraction of groundwater to a treatment plant, which could be operated along similar principles to process plant for the treatment of nuclear plant aqueous discharges. EA (1999) classifies the range of abatement technologies for pre-treating effluent releases to water from nuclear plants into several groups, principally exploiting either physical particulate properties or chemical properties. The range of techniques includes:

- Delay, hold-up and outgassing: the use of delay tanks to hold the liquor until three or four half lives for the relevant radioisotope have passed, thus retaining only 10% of the original matter. This technique is only useful for shorter half-life isotopes (unlikely to be an issue with historical contamination), as the delay period could become prohibitive. Outgassing, or the removal of some isotopes by natural transition to the gas phase, and their transfer to an appropriate treatment plant. This usually occurs for some noble gases and isotopes of iodine;

- Blending: the combination of wastes into a mixture more amenable for downline treatment. Segregation of different waste streams is more commonly used than blending;

- Filtration: using an appropriate filter medium, this technique may remove particulates formed by upstream flocculation or co-precipitation, or those which may have occurred "naturally". Filtration requires a filtration medium (such as sand or alumina granules, cloth, paper, metal mesh, carbon fibres, porous/sintered metal and ceramics), a driving force to overcome the pressure differential across the filter medium, and an appropriate support structure to house the filter;

- Ion Exchange and Adsorption: the ion exchange medium removes soluble ionic species from an aqueous phase passed through it, substituting non-active ionic species for those it removes. Ion exchange will work for both cationic species, such as strontium-90, caesium-137 and cobalt-60, replacing these with sodium and calcium, as well as anionic species such as iodine-129, replacing this with chlorine. The method will not, however, operate for non-charged or non-ionic complexes. The availability of ions from solution is also affected by the "selectivity" of each ion and other factors, such as the overall waste stream chemistry. Ion exchange media can be split into organic resins and inorganic ion exchangers; some of the latter act as absorbers (they take up material from the waste stream by electrochemical action and not exchange);

- Evaporation: essentially a volume reduction technique, control of temperature and pressure can split an aqueous waste stream into a distillate, containing the vapour phase and volatile active species, such as tritium, iodine and technetium, and the "bottoms", or the undistilled waste stream containing actinides, alkali metals, transition metals and salts. Further treatment of the distillate can result in a closely controlled "clean" stream, while the concentrated waste stream can be incorporated into cement for final disposal;

- Co-precipitation: this involves the conditioning of the waste stream, usually involving pH adjustment, the addition of a suitable soluble carrier species, such as ferrous sulphate, and the addition of an alkali. This results in the formation of a floc through precipitation of the soluble carrier, which may then scavenge active species through co-precipitation into the floc, replacing the iron, or entrainment of particulate matter within the floc. The floc is then removed, commonly using a filtration stage. Common co-precipitants used include barium sulphate (for strontium-90), organic sulphides (for transition metals, including iron, as sulphides), lanthanide oxalates (for actinides), sodium tetraphenylborate (caesium-137 and 134), calcium oxalate (actinides), copper ferricyanide (transition metals) and nickel hexacyanoferrate (caesium-137 and 134);

- Precipitation: without the required addition of a carrier, this technique involves the adjustment of the pH to precipitate out transition metals, where iron may precipitate out to form iron oxide/hydroxide or sulphides, and thus scavenge for active nuclides as described above;

- Solvent Extraction: often used for the separation of different active species, such as the separation of actinides from lanthanide's, and only on an experimental basis for low-level contaminated waste streams. Solvent extraction involves four key stages, including initial conditioning to achieve the optimum pH, oxidation state/valency of the various species, formation of a nuclide-organic complex, preferential uptake of the organic complex from the waste stream by addition of a suitable organic compound and the separation of the two liquid phases;

- Electro-chemical and electro-physical methods: these involve the separation of nuclides from the waste stream on the basis of their electrical properties, including the electric charge of ionic species, and the surface charge, or zeta potential. Many of these techniques are only at the pilot plant/test stage, and have not been applied to the treatment of waste streams. The techniques include electroflotation and electroflocculation, electro-osmotic (electrokinetic) dewatering, electrical membrane cleaning, electrochemical ion exchange, electrodialysis, electrodeposition and electroprecipitation;

- Centrifuging and Hydrocycloning: these processes exploit the physical properties of solid particulates within the waste stream. Centrifuging uses rapid rotation to force the waste stream against a filter wall, through which only effluent below the specified filter size can pass. Hydrocyclone methods inject the effluent into a conical cyclone, where particulates above the cut point are forced to the wall and discharge as the underflow, and those below the cut point discharge to the overflow;

- Reverse Osmosis: this technique is not used for large-scale, low-level liquid processing. Essentially, effluent is pumped into a reaction vessel and the active species pass across a semi-permeable membrane into a second, more active effluent. The technique separates species on the molecular scale as opposed to the size of particles;
- Oil Separation and Incineration, and other organic waste treatments: usually as the first stage in an effluent treatment process, oil separation is performed to remove oily liquids and prevent their fouling successive process stages. More complex oily liquids can be broken down for further treatment using hydrolysis, UV photochemical oxidation, wet oxidation or fluidised bed incineration.

The Guidance Note goes on to highlight the use of various technologies across the UK nuclear industry. Examples of such systems are the British Nuclear Fuels Ltd. (BNFL) Enhanced Actinide Removal Plant (EARP), the Separated Effluent Treatment Plant (SETP) and the Site Ion Exchange Effluent Plant (SIXEP). BNFL (1997) summarises these plants.

Further information on advanced cement solidification systems can be found in Nakashima *et al*, (1993), in which innovations to the established method of immobilising sludges and secondary waste streams from effluent treatment technologies are presented. Laboratory scale experiments on the recovery of uranium from waste effluent sludges have taken place, and are documented in Sugai *et al*, (1993), where a two-stage process of decontamination, using warmed nitric acid digestion of the sludge, followed by the recovery and refining of the uranium. This latter stage was carried out with a nuclear industry accepted method of TBP/n-dodecane extraction to extract uranium from the leaching solution.

With reference to actual field trials of "pump-and-treat" technology for the remediation of radioactively contaminated groundwater, EM-DOE (1997) contains a summary of the initiation of an ITRD technical advisory group on the Tuba City ITRD project. Formerly a uranium milling site, the Tuba City site has groundwater contamination of the underlying sandstone aquifer with sulphates, nitrates and heavy metals, including uranium, lead and molybdenum. The technical advisory group is currently suggesting innovative alternatives to enhance a pump-and-treat system to be installed at the site.

Bostick *et al* (1997) presents the initiation of a programme to evaluate improvements in the removal of strontium-90 and caesium-137 using chabazite/zeolite ion exchange methods. The objective of this study is to improve existing and innovative technology to reduce the production of secondary waste materials. Another ion exchange method is detailed in Feiler *et al*, (1995), which found that an immobilised algal biomass (AlgaSORB) had a high affinity for radionuclides and heavy metals contained in contaminated groundwater passed through it, in particular chromium, mercury and uranium. The resin exhibited high selectivity for the relevant metals, and was run as a process demonstration along the lines of established ion exchange processes.

Hanford Tank Wastes were used by Hendrickson *et al* (1998), in applying innovative Resourcinol-Formaldehyde, IONSIV-IE911 crystalline silicotitanate and SuperLig 644 ion exchange media to remove caesium-137 from solution in a number of tank liquors. The performance of these media ranged from the processing of between 14 and 1044 column volumes for a 50% breakthrough yield. Hexacyanoferrate ion exchangers are also effective in removing caesium from nuclear power plant waste streams, and Lehto *et al* (1993) presents a method for the selective separation of caesium from nuclear reactor evaporator concentrates using this ion exchange medium.

Other storage pond waters, biological shield waters and radium-containing acid waste water from uranium underground leaching were used in Sebesta *et al*, (1993), where experiments were carried out using new composite inorganic-organic ion exchangers. This work essentially involves the production of inorganic ion exchangers, for their superior selectivity properties, combined with polyacrylonitrile (PAN) as a binding polymer. Laboratory production of several ion exchangers is detailed, with the capability to separate caesium from other alkaline metals, to separate uranium from surface water and radium from drinking, fresh and saline waters. This latter application was in the treatment of in-situ underground uranium acid leaching effluents, containing a number of isotopes of radium, thorium, protoactinium and actinium, although only radium and actinium were retained on the absorber following process.

More innovative technologies include ultrasonic washing and electrodecontamination (Naud *et al*, 1993), where the principal objective was reducing the alpha emitter contamination in solid wastes. Effluents were first washed with Freon-113 in an ultrasonic bath and then electrode contaminated in a reactor vessel with nitric acid. Plutonium washings from the first phase were deposited on filters, which represented the only secondary waste from this process.

Conclusion

It is apparent from the range of references reviewed above that a wide range of radioelement recovery methods exist within the nuclear industry, in both active effluent treatment plant and contaminated area remediation studies. These methods could be allied with established chemical contamination "pump-and-treat" and hydrogeological expertise to solve a particular groundwater remediation problem, although careful selection of the method would be required with respect to the groundwater chemistry, the contaminant of concern and the environmental setting of the site.

There is considerably less information on in-situ treatment methods for radioactive groundwater contamination. Although the installation of an appropriate in-situ method may be carried out with established expertise, consideration must be given to the effects of a mass of complexed radioactive material within the ground and its future fate, especially where future soil chemistry and daughter products are concerned.