

Evidence

Verification of remediation of land contamination

Report: SC030114/R1

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Miranda Kavanagh Director of Evidence

Executive summary

Defra and the Environment Agency published the 'Model Procedures for the Management of Land Contamination' (CLR11) in 2004. CLR11 provides a technical framework for structured decision making about land contamination and identifies verification as a key part of the risk management process.

Verification is an integral component of any quality system to ensure that objectives are defined and appropriate evidence is collected and assessed to show that those objectives have been met. Modern environmental legislation places increasing emphasis on the importance of measuring the efficacy of our actions. For the purpose of remediation, CLR 11 defines verification as "the process of demonstrating that the risks have been reduced to meet remediation criteria and objectives based on a quantitative assessment of remediation performance".

This document aims to provide guidance on designing and implementing verification activities to increase confidence in the outcome of a remediation strategy. It should be used with CLR11, and links are provided throughout this document.

Four key stages are identified in the verification process:

- 1. Developing the remediation strategy planning verification is an integral part of this process and involves the review of information already available and collected during development of the remediation strategy.
- 2. Developing the verification plan including identification of the roles, responsibilities and sampling approach needed to demonstrate that remediation objectives are satisfied.
- 3. Implementation of the verification plan, with production and communication of the verification report.
- 4. Long-term monitoring and maintenance, where needed to satisfy long-term remediation objectives.

With increased media exposure and public scrutiny of environmental issues, there is a significant focus, at local and global level, on environmental decision making. This document encourages the use of an evolving conceptual model, with uncertainties being reappraised as more information becomes available. Multiple lines of evidence should be collected to support the primary risk-based remediation criteria.

Integration of lines of evidence is recommended, and this is mainly carried out using best professional judgement, on a logical basis by following authoritative guidance, and/or by establishing relationships between linked evidence during remediation planning.

As global drivers are increasingly influencing environmental decision making, for example by considering climate change adaptation and mitigation in major remediation projects, more sophisticated decision support tools are being used to help evaluate the importance of issues and justify and communicate a decision. Approaches are likely to evolve and, as they do, provide more opportunity to truly integrate the data from multiple lines of evidence in the decision making process.

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1 Introduction

1.1 Aims of this document

Defra and the Environment Agency published the 'Model Procedures for the Management of Land Contamination' (Contaminated Land Report, CLR11) in 2004 that provides a procedural framework for structured decision making about land contamination. CLR11 identifies verification as a key part of the risk management process.

This document provides guidance on designing and implementing verification activities to demonstrate the effectiveness of, and to increase confidence in the outcome of, a remediation strategy. It should be used with CLR11, and links are provided to CLR11 and other key references throughout this document.

1.2 What is verification and what are the benefits for remediation?

The terms 'verification' and 'validation' are embedded in quality management standards for the evaluation of a product, service, or system. BS EN ISO 9000:2005 provides the following definitions:

Quality - degree to which a set of inherent characteristics fulfils requirements;

Verification – confirmation through the provision of objective evidence that specified requirements have been fulfilled; and

Validation – confirmation through the provision of objective evidence that the requirements for a specific intended use have been fulfilled.

Key aspects of both verification and validation are setting pre-defined requirements and the collection of evidence to show that those requirements have been met. This is also the case where evidence is needed to show that remediation of land contamination has met defined objectives, usually to ensure that risks to human health and the environment are insignificant. For the purpose of remediation, CLR 11 defines verification as "the process of demonstrating that the risks have been reduced to meet remediation criteria and objectives based on a quantitative assessment of remediation performance".

There is increasing scrutiny of approaches to remediation and urban regeneration that has led to some high profile inquiries into the standard of remediation (for example De Zylva *et al.*, 2000). It is now widely accepted that assessing the concentration of a contaminant in a few samples against a target concentration may not be sufficiently robust to be confident in the outcome of a remediation project. This is particularly the case where complex remediation processes are applied to situations involving either heterogeneous strata and/or difficult contaminants.

The implementation of the European Council Directive on the Landfill of Waste 1999/31/EEC (LFD) has led to an increase in the cost of disposal of contaminated soil, particularly when classified as hazardous waste. This has created a more favourable economic market for on-site treatment of contaminated soil and groundwater. But significant barriers to the use of treatment technologies have been reported from the USA (United States Environmental Protection Agency, USEPA, 2000a) and

internationally (USEPA, 2002), even where such technologies are supported by a reasonable track record (see Box 1.1 below).

Box 1.1 Problems with the uptake of remediation technologies that may be addressed through verification.

- Remediation criteria are often ill-defined and inconsistent, and can be unrealistic for the chosen technology.
- Uncertainty related to soil heterogeneity.
- Uncertainty related to contaminant distribution.
- The treatment process may be poorly understood or communicated.
- Performance may be difficult to extrapolate from one site to other sites.
- Uncertainty over timescales necessary to achieve remediation objectives.

The use of an evolving conceptual model and multiple lines of evidence, as proposed in this document, is intended to address the uncertainties associated with remediation performance, including those identified in Box 1.1. If addressed effectively, this approach will provide an evidence-base to increase confidence in the outcome of implemented remediation strategies.

Key benefits that may be obtained by appropriate verification of remediation include:

- Demonstration of compliance with legal and contractual requirements.
- Evidence for corporate or government reporting purposes.
- Evidence to regulators, landowners and other interested parties that remediation has met agreed targets in both the long and short term.
- Greater confidence for future owners and generations in the quality of remediated land.
- Better understanding and increased confidence in the efficacy of innovative treatments.
- Identification of failed remediation where occupants of the land would continue to be exposed to unacceptable risks or landowners to liability.
- Potential cost savings focussing on the collection of appropriate and necessary data to satisfy specific remediation criteria.
- Better understanding of the sustainability of different remediation techniques (economic, social and environmental performance).

1.3 Drivers for verification of remediation

Verification is an important aspect of remediation under a range of regulatory and voluntary contexts. These include:

- Redevelopment of land under the planning regime¹.
- Regulatory intervention under the appropriate statutory contaminated land regime.
- Action to remedy harm under an Environmental Permitting Regulations (IPR) enforcement notice.
- Action to remedy water pollution under a Works Notice (Anti-pollution Works Regulations 1999).
- Action to remedy damage under the Environmental Liabilities Directive / Environmental Damage Regulations 2009.
- Voluntary remediation, including management of potential liabilities by responsible site owners.

In each case there is a need for the problem-owner to communicate with a range of interested parties, that may include regulators, local communities, financial and insurance providers and shareholders, on the success or otherwise of a remediation strategy.

1.3.1 Verification and the recovery of waste

A voluntary industry code of practice has been published to "aid decision makers in identifying if they are dealing with waste and when waste has been fully recovered" (<u>http://www.claire.co.uk</u>) for use in England and Wales. This code of practice requires that a verification plan forms part of the remediation strategy or design statement and a verification report must be completed to show that materials are dealt with appropriately.

Environmental regulators are guided by case law and take consideration of legal opinion with regard to when a waste has been fully recovered and no longer requires waste regulatory controls. An up-to-date position on waste and recovery should be sought from the respective web sites:

for England and Wales:

http://www.environment-agency.gov.uk/business/sectors/32731.aspx

for Scotland:

http://www.sepa.org.uk/land/contaminated_land/remediation_activities.aspx

for Northern Ireland:

http://www.ni-environment.gov.uk

¹ Planning Policy Statement 23: Planning and Pollution Control - Annex 2: Development on Land Affected by contamination (PPS23)

⁽http://www.communities.gov.uk/index.asp?id=1143923)

1.4 Consultation with the regulator

CLR11 identifies various stages of consultation throughout the risk management process. It states that "meaningful dialogue with all stakeholders is key to the successful outcome of risk management projects and is essential in relation to regulators who have specific statutory duties and powers for health and environmental protection". But the mechanism for dialogue with regulators will vary. This guidance identifies some key contact stages, consistent with CLR11, but a specific mechanism for communication and approval, if within the regulator's remit, should be established on a case-by-case basis having regard to the voluntary or regulatory drivers for remediation.

1.5 Structure of the document

This chapter has set out the background to, and drivers for, verification of remediation of land contamination. The following chapters are to be used with chapters 3 and 4 of CLR11. A number of process diagrams are provided that follow or expand on those used in part 2 of CLR11.

Chapter 2 sets out the role of verification in the development and implementation of a remediation strategy. It identifies the key steps in verification, and links verification activities to existing standards.

Chapter 3 sets out the key elements of information review to support the development of the remediation strategy. This chapter supports the use of multiple lines of evidence to collectively demonstrate that remediation criteria and objectives are met.

Chapter 4 identifies the key elements of the monitoring, sampling and inspection activities that should be set out in a verification plan within a quality management framework.

Chapter 5 provides guidance on implementation of the verification plan and production of a verification report - a complete record of all remediation activities on site and the data collected to support a decision on whether remediation objectives are achieved.

Chapter 6 provides guidance on long-term monitoring and maintenance, if needed, to meet long-term remediation criteria and objectives.

Chapter 7 discusses the role of this document in promoting both transparency and confidence in knowledge-based remediation and identifies initiatives and research needs within and outside the UK that may help to advance effective verification methods.

Appendix A provides information maps to key information sources that support the process highlighted in the chapters above.

Appendix B provides information on lines of evidence that may be used to support remediation criteria that may be used to demonstrate the performance of remediation.

2 The verification process

2.1 Verification of remediation

For remediation, the fundamental purpose of verification is to evaluate whether identified risks are successfully managed over pre-defined timescales to meet the objectives of the remediation strategy, based on a quantitative assessment of remediation performance. Verification is an essential part of project closure, but its planning should not be left to the end. Indeed, its planning is a key part of developing the remediation strategy.

2.2 What is the remediation strategy?

CLR11 defines the remediation strategy as "a plan that involves one or more remediation options to reduce or control the risks from all the relevant pollutant linkages associated with the site". The development of a remediation strategy will be carried out during options appraisal (see Chapter 3 of CLR11) and consider the practical implementation of the options proposed to meet the remediation objectives. Issues that should be considered include:

- How a site should be zoned or works phased to accommodate both remediation and redevelopment needs.
- How the remediation strategy is to be verified, including consideration of phasing for release of areas for development and the end-point objectives of monitoring.
- What preparatory works (for example baseline monitoring, treatability or pilot studies) need to be factored in at an early stage.
- What evidence is needed to support the reuse of materials on-site, if appropriate, as part of the remediation strategy.

Verification planning and implementation are therefore central to the successful completion of a remediation strategy.

2.3 Verification – planning to implementation

Quality assurance is an important project-specific aspect of quality management throughout the planning and implementation of the remediation strategy. There are two key features (from CLR11):

- The need to provide an accurate and permanent record of remediation and the standard it has achieved (the verification report).
- Remediation may need maintenance and/or monitoring to achieve or demonstrate on-going effectiveness.

A precursor to the first of the above is the development of a verification plan. Descriptions of the verification plan and verification report are given in CLR 11 and reproduced in Box 2.1 below.

Box 2.1 Verification definitions (from CLR 11).

Verification plan

A document that sets out the requirements for gathering data/evidence to demonstrate that remediation meets the remediation objectives and remediation criteria. It includes monitoring, sampling and testing criteria, and identifies all those records that should be retained to demonstrate compliance within the specification (e.g., field monitoring data, laboratory data, level surveys above and below capping layers).

Verification report

A document that provides a complete record of all remediation activities on site and the data collected as identified in the verification plan to support compliance with agreed remediation objectives and criteria. It also includes a description of the work (as-built drawings) and details of any unexpected conditions (e.g. contamination) found during remediation and how they were dealt with.

The verification plan is therefore a monitoring and sampling plan to meet a specific set of objectives and criteria. Where collection and analysis of soil/water/gas samples is the appropriate strategy to verify remediation, guidance on developing sampling plans is already available in a number of standards (see INFO 2-1). In particular, the standard for characterisation of waste (BS EN 14899:2005) is referred to in this document as:

- The range of sampling situations for remediation of soil is similar to that for industrial processes (moving stream, static stockpile, etc.) that produce solid waste residues.
- The standard is supported by comprehensive technical reports (see INFO 2-1) that can be used to support the selection of sampling requirements for any testing programme.

BS EN 14899:2005 provides a logical process and detailed technical information for use when developing a verification plan. Other standards (INFO 2-1) should also be used, particularly where specialist techniques or other media are involved. In particular, BS EN ISO 5667 and CIRIA (2007) provide guidance for water and ground gases respectively. Table 2.1 summarises the key steps in the verification process that are linked to standards and are discussed in the following chapters.

It should be noted that this guidance does not address compliance with permit conditions other than those that relate to remediation objectives (such as some planning conditions). Reference should be made to the relevant regulatory guidance for information on environmental permitting.

2.4 Summary

This chapter sets out the role of verification in the development and implementation of a remediation strategy. It identifies the key steps in verification, and links verification activities to existing standards. Subsequent chapters will discuss those steps in more detail, linked throughout to CLR 11.

Step (in this document)	Activities	Equivalent step in BS EN 14899: 2005
Identify involved parties (Section 3.2)	Assign project manager Identify project team Define roles and responsibilities	Key Step 1; Clause 4.2.1 – Involved parties
Identify objectives and define technical goals (Section 3.3)	Identify remediation objectives and develop measurable remediation criteria	Key Step 1; Clause 4.2.2 – Objectives of the testing programme
Identify generic level of testing	Incorporated into remediation criteria above	Key Step 1; Clause 4.2.3 – <i>Testing level</i>
Review existing information (Sections 3.4 to 3.6)	Revise conceptual model Develop lines of evidence Identify additional data needs	Key Step 1; Clause 4.2.5 – Background information on material
Identify constituents to be tested (Section 4.2.)	Identify contaminants and other parameters	Key Step 1; Clause 4.2.4 – Identify constituents to be tested
Select monitoring/sampling approach (Section 4.3 to 4.6)	Define when to monitor and sample, locations, pattern and media, and the number or frequency	Key Step 1; Clause 4.2.7 – Select sampling approach
Identify monitoring/ sampling technique	Identify methods and equipment for monitoring, sampling, labelling, preservation, transport. Not addressed in detail in this report. Refer to INFO 2-1 and 4-1	Key Step 1; Clause 4.2.8 – Identify sampling technique
Identifying health and safety precautions	Legislative and site requirements, risk assessments, experience and training Not addressed in this report. Refer to INFO 2-1 and relevant guidance from the Health and Safety Executive	Key Step 1; Clause 4.2.6 – <i>Health and</i> <i>safety</i>
Identify data management techniques (Section 5.1.1 and Section 5.3.1)	Identify unique numbering system, sampling recording system, chain of custody forms, data assessment methods	Key Step 2; Clause 6.2 – <i>Sampling record</i>
Implement the verification plan (Section 5.1 and 5.3.1)	Implementation, including review of data/evidence either periodically or against milestones	Key Step 2 to 7
Produce verification report (Section 5.3)	Analyse data against objectives (utilising statistical testing methods), review conceptual model, report and communicate results.	Key Step 7 – Produce overall measurement report

Table 2.1Key steps in the verification process.

3 Review existing information

3.1 Verification and the remediation strategy

Planning the remediation strategy will follow on from earlier stages of risk assessment and options appraisal, as detailed in CLR11. A significant amount of information may therefore be available to be used in the design of a remediation strategy and to develop a clear understanding of the verification needs. Such information should be reviewed to identify what additional data are needed and, following iterations if necessary, to ensure that sufficient information is available to proceed with the design of sampling activities necessary to provide the evidence to assess whether remediation objectives are achieved (see Chapter 4 of CLR11).

This chapter details the elements of the review process that:

- Identify roles and responsibilities (Section 3.2).
- Identify the remediation objectives and criteria (Section 3.3).
- Review of the conceptual model for remediation (Section 3.4).
- Establish lines of evidence (Section 3.5).
- Involve consultation with involved parties (Section 3.2).

This process is outlined in Figure 3.1 and is to be used in association with Figure 3C of CLR11.



Figure 3.1 Review process to support verification planning as part of developing a remediation strategy.

3.2 Who does what?

Remediation will usually come within the requirements of the Construction (Design and Management) Regulations 2007, with specific duties for clients, designers and contractors to ensure that appropriate arrangements are put in place so that the work can be carried out without risk to the health and safety of any person. A similar approach should also apply to environmental management of remediation, including verification, and that all activities are carried out by suitably experienced personnel.

The preparation of the verification plan may be taken forward by the same party that develops the remediation strategy or a different designer may be appointed. The roles and responsibilities of consultants, contractors and specialist sub-contractors carrying out verification activities must be clearly defined in the verification plan, including reporting procedures to be maintained throughout the project. The time and money allocated to the design of the verification plan should match the need to ensure that all necessary data can be collected in a cost-effective manner.

It may be necessary to involve specialist contractors to advise on the technical and practical implementation of verification activities. The specialist contractor will need to have a good understanding of how a particular monitoring technology works, its limitations, and the uncertainties that can be addressed through a lines of evidence approach.

Communication with a wide range of stakeholders may be needed during the remediation, and verification data may come under close scrutiny. It is therefore important to ensure that relevant data are collected and communicated in the most effective manner to both technical and non-technical parties. The robustness of the audit trail should be considered in detail, for example to avoid issues such as conflict of interest. In some cases it may be prudent that suitable independent experts are appointed to scrutinise the verification report.

3.3 What are remediation objectives and criteria?

3.3.1 Remediation objectives

CLR11 defines remediation objectives as "site-specific objectives that relate solely to the reduction or control of risks associated with one or more pollutant linkages that are demonstrated, through risk assessment, to represent unacceptable risks".

Remediation objectives will have been set during options appraisal (CLR11 Chapter 3) and reviewed to ensure that they remain valid after a feasible remediation strategy has been selected. The selected objectives should be achievable, having regard to risks to the identified receptors, costs and benefits (for example Environment Agency, 1999), technical feasibility, sustainability criteria (CL:AIRE, 2009), and current or proposed use of the site. They will usually focus on breaking the pollutant linkages with one or more of the following outcomes:

- A decrease in contaminant mass or concentration.
- A decrease in contaminant mobility or toxicity.
- Effective containment of the contaminant.
- Management of the pathway or the receptor.

3.3.2 Remediation criteria

CLR11 defines remediation criteria as "measures (usually, but not necessarily, expressed in quantitative terms) against which compliance with remediation objectives will be assessed". Quantitative levels may be based on one or more of the following approaches:

- Adopting generic assessment criteria.
- Adopting site-specific values from quantitative risk assessment.
- Deriving site-specific criteria, for example based on the removal of a stated proportion of the total contaminant mass or reduction in flux, toxicity or mobility.
- Deriving engineering-based criteria (for example the thickness and permeability of a cover system or slurry wall, or documentation on the location and volume of treated soil).
- Deriving site-specific use-based criteria (for example by restricting the permitted uses that a site can be put to in property deeds or by legal covenant).

The quality of evidence needed to make a decision on whether remedial objectives have been achieved is an essential consideration throughout the verification process. Data collection can be poorly focused and extremely variable in the absence of clearly defined remediation standards and a sound conceptual model. Too often in the past remedial criteria have been set, and agreed, with little or no documented evidence for how compliance should be measured or the number of samples that will be needed to meet a desired level of confidence.

Each remediation criterion must therefore be clear and contain relevant information on:

- The level of testing in this case, usually to demonstrate compliance with the remediation criterion.
- The quantitative limit and summary statistic (for example a mean concentration at 95 per cent confidence level).
- The population to which it applies (for example all soil in a defined area to 3 metres depth).
- The required levels of detection, bias and precision.
- Where appropriate, the timescale and/or frequency of monitoring (for example weekly measurement of soil gases for 3 months after active remediation ceases).

Criteria may need to be set for short, medium or long-term compliance, depending on how pollutant linkages are managed following treatment. The need for long-term monitoring, and a staged approach to verification and project closure should be considered particularly where containment technologies, some *in situ* groundwater treatment, pump and treat (both rebound issues), or monitored natural attenuation is proposed. An example is given in Box 3.1.

Timescales should be clearly stated when setting specific criteria and may initially be selected on the basis of predictive modelling or the outcome of a field pilot study (for example monitoring of rebound effects following active remediation such as pump and treat or air sparging). Further information on the importance of timescales is given in Section 4.3, and long-term monitoring is discussed in more detail in Chapter 6.

Key information sources on setting remediation objectives and criteria are provided in INFO 3-1.

Box 3.1 Example of objectives changing with timescale. (after Gavaskar, 2002)

Scenario

Long-term spills and leaks of chlorinated hydrocarbons at an industrial site. Complete removal of DNAPL source is impractical and diffusion into groundwater from residual DNAPL is likely to continue after *in situ* source treatment. Monitored natural attenuation is predicted to be viable for treatment of the residual contaminant.

Short-term objective

Receptor protection - maximum achievable mass removal (based on relationship between cost and removal – diminishing return), to minimise potential for movement of contaminants (for example mobile NAPL), dissolved phase plume generation or the duration over which contaminants will persist.

Criteria based on mass removal (e.g. cumulative contaminant mass removed for cosolvent flushing, cumulative reaction product mass for chemical oxidation), and/or beforeafter comparison of contaminant concentrations in soil.

Intermediate-term objective

Receptor protection – decrease in contaminant concentration at compliance points

Achieving remedial criteria (e.g. contaminant concentrations in groundwater) at compliance point/s. Supporting lines of evidence may include measurement of plume (static, shrinking?), evidence of viable geochemical conditions or of viable microbial activity, stable isotope data to support natural attenuation of the contaminant.

Long-term objective

Receptor protection - decrease in contaminant concentration in source zone

Achieving risk-based remedial criteria in the source area.

3.4 Does the conceptual model apply to the remediation strategy?

In an ideal world remediation decisions will be made on an absolute knowledge of contamination at a site and the dynamic processes already going on and about to be initiated through remediation. As the ideal is never achieved we need a means to capture the boundaries of our knowledge.

CLR11 highlights the importance of the conceptual model as a basis to support the identification and assessment of pollutant linkages throughout the risk assessment process. The conceptual model will be evolved (for example Rossabi *et al.*, 2000) as more data and information are gathered to reduce uncertainties.

This revision should continue through all risk management stages until it is shown that remediation objectives have been achieved. All further references to the conceptual model in this document relate to its evolution through development and implementation of the remediation strategy.

The conceptual model, therefore, provides a means of helping all parties to understand the factors that must be monitored and quantified before, during and after remediation. This will include identifying problems that may affect the remediation strategy and hence verification activities, for example unforeseen conditions, heterogeneity of made and natural ground, and variability of groundwater or contaminants including soil gases. It also needs to be time-bound, for example do you need to consider whether site or climatic conditions are likely to change during the design life of the remediation?

It is important to routinely challenge the conceptual model, and a review process outlining the milestones (perhaps linked to phased release of land for development) or trigger points (for example failure to meet a specification for treated soil) should be included in the verification plan.

Box 3.2 shows an example of how reviewing the conceptual model has helped to manage a long-term remediation process, in this case pump and treat (Hoffman *et al.*, 2003).

Box 3.2 Reviewing the conceptual model during pump and treat (after Hoffman *et al.*, 2003)

Context

Revision of the conceptual model based on field data collected during seven years of pump and treat remediation of volatile organic compound (VOC)-contaminated groundwater.

Findings

Contaminant plumes can be divided into two distinct zones:

Source area - high concentration VOCs in both fine and coarse soils;

Distal area – VOCs orders of magnitude lower concentration, and primarily in coarse soils with limited diffusion into adjacent fine soils

Implications for verification

Set different objectives for source and distal zones, with hydraulic isolation of the sources. Achievement of objectives in distal zones may be expedited at lower cost and over shorter timescales.

3.5 What are lines of evidence?

Lines of evidence are "data sets of key parameters that support the agreed remediation criteria to demonstrate the performance of remediation" (CLR11). The concept was introduced by the National Research Council (1993) for *in situ* bioremediation; developed from the premise that, a reduction in contaminant concentration alone does not provide unequivocal evidence that it is a result of a bioremediation process. Other factors such as volatilisation, dispersion, dilution or sorption may have a significant bearing on documented loss of contaminant, and also on the possibility for the concentrations to increase again some time in the future (rebound).

The Committee on *In Situ* Bioremediation (NRC, 1993) recommended a strategy for evaluating the performance based on converging lines of independent evidence to include:

- Documented loss of contaminants from the site.
- Laboratory assays showing that micro-organisms from site samples have the potential to transform the contaminants under expected site conditions.
- One or more pieces of information showing that the biodegradation potential is actually realised in the field.

A similar approach is now commonly applied to monitored natural attenuation (MNA) (American Society For Testing And Materials (ASTM), 1998, Environment Agency 2000). For MNA three lines of evidence have been applied:

- Documented loss of contaminant mass or reduction in concentration.
- Geochemical and biochemical indicators that demonstrate which natural attenuation process(es) is causing the mass/concentration decrease.
- Microbiological and isotopic data to support the occurrence of biodegradation.

3.5.1 How can lines of evidence be applied?

Lines of evidence are proposed to ensure the collection of effective data for the purpose of verification of a remediation (see INFO 3-2 for information sources). Lines of evidence should be established from the conceptual model during development of the remediation strategy.

In most cases the primary evidence will be a documented reduction in contaminant concentration to an agreed criterion, using accredited laboratory data. Significant uncertainty may still remain when variability (for example, soil heterogeneity, contaminant or reagent distribution) is fully considered, but the cost of analysis can become prohibitive. Additional lines of evidence can therefore be proposed to reduce uncertainty and build confidence that remediation objectives are achieved in a more cost-effective manner. This can be achieved by a number of means, for example to increase data density or to demonstrate that the remediation process is responsible for the observed change.

The lines of evidence should therefore be the principal drivers for the collection of verification data and must be regularly reviewed throughout the course of a remediation to ensure that they are still valid and sufficient to meet the overall objectives of the remediation strategy. Some common examples of the evidence that may be collected to support primary evidence are given in Box 3.3.

Box 3.3 Examples of lines of evidence. Field measurements to support laboratory analysis. Field measurements to test model predictions. Data on the physical properties of barrier systems. Data to show that contaminants have been immobilised. Data on intermediate and final breakdown products, such as evolution of carbon dioxide during biodegradation. Concentration of conservative components and/or internal markers. Process parameters, e.g. pH, temperature, moisture content. Bioassays to indicate a reduction in toxicity of soil. Data to show the location and volume of treated materials. Additional sampling outside the remediation area to quantify any spread of contaminants beyond the remediation area. Geophysical survey data to delineate a contaminant plume. Data on nutrients and/or electron acceptor/donor concentrations that are required to drive a biological process. Inspection of infrastructure (for example fencing, signage) where land access or water-use restrictions are in place.

Now that we understand the lines of evidence we need to support the primary evidence, how do we put them to use? Linkov *et al.* (2009) reviewed "weight of evidence" approaches that are taken to assess multiple information sources used for risk assessment. The approaches are reproduced in Table 3.1 below with comment on their applicability to remediation.

Approach	Description	Applicability to remediation
Listing evidence	Presentation of individual lines of evidence without attempt at integration	Adds little benefit to remediation decision-making.
Best professional judgement	Qualitative integration of multiple lines of evidence	Subjective integration – may be defensible on a case-by- case basis.
Causal criteria	A criteria-based method for determining cause and effect relationships	An example is correlating operating conditions with remediation performance or correlating hydraulic conductivity with moisture content-dry density curves for engineered containment.
Logic	Standardised evaluation of individual lines of evidence based on qualitative logic methods	Uses a previously outlined method, for example the guidance on monitored natural attenuation (Environment Agency 2000).
Scoring	Quantitative integration of multiple lines of evidence using simple weighting or ranking	Not likely to be used, although statistical methods such as double sampling or ranked set sampling (Gilbert, 1987; USEPA, 1995) may be used to integrate large (field observations) and small (laboratory data) data sets.
Indexing	Integration of lines of evidence into a single measure based on empirical models	An example is integration of assays to produce an index of the biological quality of a treated soil, for example Dawson <i>et al.</i> (2007).
Quantification	Integrated assessment using formal decision analysis and statistical methods	This is the ultimate level of "weight of evidence" and, for remediation, is currently aspirational and in many cases unnecessary.

 Table 3.1 "Weight of evidence" approaches (after Linkov et al., 2009).

This is an evolving area of environmental decision-making, and the aim should be to apply as objective a method as possible to integrate individual lines of evidence. In many cases this will rely on sound, and defensible, professional judgement. A key to integration will be to maximise the use of information collected before or in preparation of the remediation strategy to understand how best individual lines of evidence can be linked. The method used to link evidence should be documented in the verification plan.

3.6 What is the role of treatability studies in the verification process?

As emphasised in Chapter 1, the verification process commences from the outset of the design of the remediation strategy. Treatability studies are usually carried out during options appraisal or in the design stage to provide additional information on the viability of a remedial option or to support the design of a remediation strategy. Guidance on conducting treatability trials is available (see INFO 3-2), but does not specifically address the importance of treatability trials to verification planning.

Treatability studies conducted in the laboratory or in the field may be used to address a number of questions that are relevant to verification planning, in particular to confirm that proposed lines of evidence are appropriate. These include:

- Is the proposed treatment potentially viable under expected site conditions?
- What are the critical controls or operating windows (for example pH, temperature, nutrient levels, moisture content) on the efficacy of the remedial process?
- What are the order and rate of reaction?
- What reaction by-products are produced and in what phase/s?
- Are viable microbial degraders present in the soil or groundwater, and if so, what are the optimal conditions?
- Is leaching behaviour likely to change with time or under changing environmental conditions (for example change in pH or groundwater levels) (British Standards Institution, 2008)?
- Are soil geotechnical properties likely to change, and will this impact on structures or services?
- Will injection pressures impact on soil/aquifer properties?
- Will spacing of injection/extraction points be sufficient to reach the contaminants or affect contaminant migration (for example gases)?

This information will lead to an evaluation of the likely effectiveness of remediation given the site conditions and nature of contaminants. Appropriate lines of evidence can then be developed to test the predicted performance of the remediation. Where possible relationships should be established, and documented, in order to identify qualitative or quantitative methods to integrate some or all of the lines of evidence.

Such studies may be particularly applicable to *in situ* technologies where the transfer of knowledge about the performance of the technology between sites can show poor correlation as a result of variability between sites. An example of how a field trial can be used in verification planning is shown in Box 3.4 below.

Box 3.4 Testing lines of evidence through a field trial.

Scenario

A laboratory treatability study showed that the degradation of carbon disulphide (CS_2) was feasible using chemical oxidation. A field trial was commissioned to demonstrate that this technology could be safely applied *in situ* for the treatment of CS_2 in soil and groundwater.

The site is in a residential area on a former rayon manufacturing plant. A site investigation revealed heterogeneous sandy and gravely clay made ground over sandy and gravely clay overlying weathered sandstone. Groundwater was struck at around 1-1.5 m below ground level in the treatment area. The shallow groundwater was not continuous across the site.

Remediation Criteria

As this was a "proof of concept" trial no quantitative criteria were set. One of the objectives was to evaluate the contaminant mass removal that was achievable – often used as a remediation criterion in a source area.

Lines of Evidence

Multiple lines of evidence were established for the trial using both laboratory and field analyses. The primary line of evidence is addressed by laboratory analysis for CS_2 in soil and groundwater samples.

Field measurement of CS_2 using a Membrane Interface Probe (MIP) and field laboratory gas chromatography were carried out to support the primary evidence, thereby improving data density in heterogeneous ground.

Additional sampling was carried out to quantify any spread of CS_2 beyond the treatment area.

Adequate control over the treatment was assessed using measurement of temperature and vapours, and geochemical indicators (electrical conductivity and oxidation-reduction potential) were used to indicate that chemical oxidation was responsible for any observed reduction in CS_2 concentration.

Sampling Plan

High sampling density was proposed, and a 1 m grid was set out to accurately locate both injection and sampling points. Key sampling elements:

Baseline sampling- 2 m offset grid,

MIP and sampling between injections (injections were phased to assess to potential for undesirable reactions – volatilisation or temperature increase), and

Post-treatment MIP and sampling.

Data Assessment

Summary statistics were analysed, and upper 95% confidence limit concentrations show 90% reduction in both soil and groundwater, and evidence of mass reduction beyond the treatment area. Spatial plots were used to show CS_2 distribution in soil and groundwater before and after treatment.

The Environment Agency acknowledges Arcadis GMI and Akzo Nobel UK Ltd. for providing this case study information.

The key learning points from this trial that can be taken through to verification planning are:

- 1. Consideration of when to sample and the need to establish good baseline data.
- 2. The value of field measurements in improving the spatial density of data in heterogeneous ground.
- 3. Being able to demonstrate that the treatment has performed in a controlled manner and as predicted through a suite of measurements within and beyond the treatment area.

3.7 Summary

CLR 11 details the reporting requirements that include a decision record as detailed in Box 3.5 below.



This chapter emphasises the need for a review of relevant information in order to support development of the remediation strategy. Additional data needed to complete the remediation strategy will have been identified, possibly including data from treatability studies or predictive models. Key outcomes from this stage of the verification process are:

- Development of remediation criteria, including data quality requirements, to enable compliance with remediation objectives to be measured.
- Review of the conceptual model to take into account the remediation process.
- Establishment of lines of evidence to support compliance with criteria and ensure that the data to be collected are 'fit for purpose'.
- Identification of methods to be used to integrate, where possible, individual lines of evidence.

Sources of information must be clearly stated and uncertainties identified (and where possible quantified). All decisions must be justified to relevant parties and such justification should be included in the decision record.

4 Select monitoring approach

4.1 Design a monitoring approach for verification

Chapter 3 described a process for reviewing information to assess what verification activities are needed to support the remediation strategy and ultimately prove that remediation objectives have been met. CLR11 then describes the stages of implementation of risk management (see CLR11 Chapter 4), comprising:

- Preparing the implementation plan.
- Design, implementation and verification.

The implementation plan (CLR11 Figure 4A) will be prepared to translate the remediation strategy into a set of activities that will deliver the overall objectives (remediation, management and other technical objectives) of the remediation strategy. The implementation plan should set out all management, legal, technical and financial activities needed to implement the remediation strategy and should be subject to consultation with relevant parties before proceeding to remediation design.

The agreed implementation plan provides a clear way forward to design the remediation (including specification, drawings and contract documents, obtain the necessary permits and agreements, procure services and implement the remediation strategy).

In most cases the boundaries between development of the remediation strategy, implementation plan and detailed design are dovetailed rather than sequential and the whole package of plans referred to above will be produced as a single remediation strategy document that will include a verification plan.

This chapter discusses the key steps in developing a monitoring approach as part of the verification plan, namely:

- Defining contaminants and other parameters of interest (Section 4.2).
- Defining when to monitor/sample (Section 4.3).
- Defining the locations, pattern and media for monitoring/sampling (Section 4.4).
- Defining the duration and frequency of monitoring/sampling (Section 4.5)
- Defining the number of samples (Section 4.5).
- Quality assurance/quality control measures to ensure that data are fit for purpose (Section 4.6).
- Producing the verification report (Section 4.7)
- Determining the need for long-term monitoring and maintenance (Section 4.3.5)

An overview of these steps is shown in Figure 4.1. Key information sources on monitoring/sampling approaches are given in INFO 2-1 and INFO 4-1.



Figure 4.1 Designing a verification plan.

4.2 Determinands

A list of determinands should be included, based on the remediation criteria and lines of evidence (see sections 3.3 and 3.5).

4.2.1 Contaminants

The primary evidence collected for many remediation processes is usually to demonstrate that, after remediation, contaminant concentrations do not exceed remediation criteria. Criteria may be based on total content in a soil, dissolved phase in groundwater or surface water, gaseous phase in soil or leachable content in a soil. Contaminant properties therefore need to be carefully considered to ensure that appropriate data is collected. Some contaminant properties that may need to be considered when developing a verification plan are summarised in Table 4.1.

Property	Comment
Is the contaminant soluble in water?	A line of evidence may relate to immobilisation or solubilisation of a contaminant. These processes may be reversible.
Is the contaminant immiscible or partly miscible with water?	A non-aqueous phase liquid (NAPL) can be difficult to locate or capture and may provide a source of dissolved phase contaminants to groundwater. Verification of an <i>in situ</i> remediation will need to consider rebound effects.
Will the contaminant strongly sorb to soil (clay or organic matter)?	Sorption is reversible and factors such as change in environmental conditions (pH, redox), competition for sorption sites and sorptive capacity may need to be considered. Desorption may give rise to rebound effects.
Is the contaminant volatile?	The verification programme should take account of phase transfer through volatilisation, both in terms of mass balance and also potential harm from volatile contaminants (for example benzene, vinyl chloride).
Can the contaminant exist in different oxidation states?	A line of evidence may relate to the transformation of a contaminant to a more or less toxic or mobile form, for example Cr ⁶⁺ / Cr ³⁺ . Such transformations may be reversible.
Is the contaminant degradable?	Breakdown products as a result of the remediation technique and/or natural processes may provide lines of evidence that the remediation process is on-track.
	Evidence may be required to demonstrate that the effects of any hazardous breakdown products are mitigated.

Table 4.1 Contaminant properties that may influence verification sampling.

Remediation criteria often relate to contaminant concentrations, obtained by laboratory analysis and measured to prescribed performance criteria (for example MCERTS for soil). It is important to ensure that the selected methods meet data quality objectives (for example, there is no merit in gathering data where the limit of detection is equal to or higher than the remediation (compliance) criterion).

In some cases an additional line of evidence may be field measurement of contaminant concentrations. Such testing, if used with an appropriate sampling and analytical plan and in conjunction with laboratory analysis, may have significant advantages, including (Environment Agency, 2009):

• Access to real-time data – by having access to real-time data while on-site, real-time decisions may be made.

- Improved data quality by greater sample density and improving the quality of data, and hence increasing the confidence in the risk management process.
- Improved data quality by avoiding potential sample degradation during transport and storage (for example dissolved oxygen, dissolved iron, redox potential).
- Cost savings.

4.2.2 Other determinands to support additional lines of evidence

Other determinands may be of interest to support additional lines of evidence and a wide variety of tools are available for both *in situ* and laboratory measurement of physical, geochemical, ecotoxicological or biological properties of contaminants or contaminated media. The specific determinands of interest will depend on both the site conditions and the remediation methods being used. INFO 4-2 provides links to sources of information for the most widely used remediation technologies.

Data to support additional lines of evidence may be collected using widely available industry standards (such as temperature measurements), infrequently used techniques to support remediation in complex scenarios (such as geophysical survey or bioassays), or little used, but promising, research techniques (such as stable isotope fractionation or push-pull tracer tests). Table 4.2 shows a range of lines of evidence that have been used at both a practical and research level, and they are discussed further in Appendix B:

Measurement	Application	Reference
Geochemical indicators	MNA	Environment Agency 2000
	Chemical oxidation	ITRC 2005
	PRB	Gibert <i>et al.</i> 2007,
Biodegradation indicators	Respiration (biopile)	Plaza <i>et al.</i> 2005a
	Presence of degraders in	Ferguson <i>et al.</i> 2007
	groundwater	
Process conditions	Biological treatment	
	Temperature	CL:AIRE 2005
	Air sparging	
	Dissolved oxygen	CL:AIRE 2004
	Groundwater pressure	Yang <i>et al.</i> 2005
Bioassays	Change in	Plaza <i>et al.</i> 2005b
	ecotoxicity/bioavailability	Dawson <i>et al.</i> 2007
	(for example biopile)	
Geophysical properties	Extent of plume	
	Electrical conductivity	Atekwana <i>et al.</i> 2004
	Resistivity	Watson <i>et al.</i> 2005
	Air distribution (sparging)	
	Electrical resistivity	Suthersan 1997
Geotechnical properties	Hydraulic conductivity	
	Containment	CIRIA. 1996
	S/S	CIRIA 2000
Mineralogy	Stability of mineral phases	
	Immobilisation	Wright <i>et al.</i> 2005
Tracer tests	NAPL remediation	Istok <i>et al.</i> 2002,
		Ramsburg et al. 2005
Stable isotope	In situ biodegradation	Kuder <i>et al.</i> 2005
fractionation	-	Fischer et al. 2007

4.3 When to monitor/sample

Time is a critical factor to consider when developing a sampling approach. In particular, verification data may need to be collected before, during and/or after remediation to assess:

- Conditions prior to remediation (for a comparison with closure conditions).
- Release of land for phased development.
- Whether the remediation process is proceeding as predicted.
- Temporal variability (for example, of ground gases).
- Contaminant rebound in groundwater after active remediation (Thomson *et al.*, 2008).
- Recontamination from a secondary source (for example wind-blown dust from untreated land (Clark *et al.*, 2008)).
- Long-term efficacy of containment or passive measures.
- Remobilisation as a result of environmental or climatic change.

4.3.1 Before remediation

Data may be required, to reduce uncertainties in the conceptual model, on conditions of the site before remediation where significant time has elapsed since the last intrusive investigation. This may be the case where contaminants are mobile and may have migrated, contaminants may have migrated from adjacent sites, and recent spillages or fly tipping of wastes may have occurred.

Data should always be collected on conditions before remediation where initial conditions need to be established to verify the treatment effectiveness. In some cases this will require remediation investigation/s in addition to the work carried out in the risk assessment stages. Examples of where this approach may be necessary include:

- Establishing baseline (T_o) conditions, for some *ex situ* biological or chemical processes, where contaminant distribution is likely to change due to excavation, stockpiling and blending for example a biopile or turned windrow.
- Establishing baseline (T_o) conditions, for an *in situ* contaminant plume or ground gas concentrations and flux before remediation.
- Measuring the extent of a contaminant plume before MNA, *in situ* remediation or source removal or treatment.
- Measuring groundwater levels and quality before installing a PRB (influence of seasonal variation should be considered).
- Measuring background (up-gradient/stream) surface water or groundwater quality and electron acceptor/donor concentrations (seasonal variation should be considered).

However there will be instances when due to management factors, for example time constraints, "baseline" conditions will not be established to a high degree of confidence. Remediation criteria may need to account for a larger factor of safety (level of confidence) should this be the case.

4.3.2 During remediation

The conceptual model may include the findings from predictive modelling and these predictions may need to be tested at milestones during remediation to ensure that remediation objectives are still likely to be achieved. In addition, the remediation performance should be tracked to assess whether remediation objectives are likely to be achieved and to optimise or improve the remediation performance.

4.3.3 Compliance testing

Compliance testing will usually be an essential component of a remediation project to demonstrate that emissions satisfy the objectives of an authorisation or permit. Such information may also be useful to satisfy specific lines of evidence (such as emission rates for mass balance calculation). It is therefore important to ensure that, where this is the case, the compliance testing data are also sufficient to meet lines of evidence data quality requirements.

4.3.4 After remediation

Confirming conditions after remediation may involve inspection, monitoring and sampling activities similar to those carried out:

- Before remediation to make a comparison of before and after conditions (for example groundwater quality, soil quality, ambient air quality).
- During remediation to test for rebound effects, for example monitoring for six months after active *in situ* remediation has ceased.

The period of post-remediation monitoring required will be site-specific and may be extended (over several months to years). McGuire *et al.* (2006) highlight the need for post-remediation monitoring. From a review of intensive remediation of 59 DNAPL sites, contaminant rebound had occurred at around a third of the sites where at least 1 year of monitoring data were available.

Alternatively, sampling activities may be one-off exercises, for example to demonstrate that all contaminated soil has been excavated or that redeposited soil meets site-specific risk assessment criteria.

The acquisition of topographic survey and inspection data may also be important for certain remediation projects, such as to support direct measurement of cover thickness or to document the location and volume of treated soil.

4.3.5 Long-term monitoring and maintenance

In many cases the duration of post-remediation monitoring/sampling is sufficiently short to enable verification to lead to project closure, with no need for further monitoring or maintenance. However, monitoring may need to be extended over a period of years, possibly decades, to demonstrate that long-term remediation objectives are achieved.

As remediation objectives can be measured against time-dependent criteria (see Section 3.3), it may be desirable to carry out verification in a staged manner against achievement of short-term, medium-term and long-term criteria. In particular, monitoring may be needed to show that passive methods, natural attenuation or long-term source-control methods perform as predicted, for example:

- Monitored natural attenuation (Environment Agency, 2000).
- Permeable reactive barrier (Environment Agency, 2002a).
- Passive and active landfill gas control systems.
- Cover systems and containment walls.
- Phytoextraction or phytostabilisation.
- Pump and treat systems.

A verification report may be prepared after a sufficient period of monitoring to meet short-term remediation objectives, but monitoring and maintenance may be required to ensure that the remediation strategy remains fit for purpose. This is an increasingly important aspect of verification where contaminant destruction, transformation or containment is managed over long timescales.

Although a project cannot be closed until all objectives are achieved, a welldocumented staged approach with key milestones provides a good mechanism to track progress against time-dependent objectives, increasing confidence that clearly set out objectives are being achieved, and to highlight the work that needs to be done in the longer term. The requirements for long-term monitoring and maintenance following remediation should be clearly set out in the verification plan. This is discussed more fully in Chapter 5.

4.4 Locations, pattern and media

Our conceptual model, in particular knowledge of the site history, soil and aquifer properties, contaminants and their distribution, and the remediation process, will guide the selection of monitoring locations and media. A key question to consider is where and at what point the pollutant linkages are being managed and therefore should be measured. Table 4.3 shows typical criteria to be considered when determining sampling/monitoring locations and media.

Table 4.3 Typical issues for selection of monitoring locations and media.

Issue	Comment
Does analysis of the data require a particular sampling pattern?	Ensure sampling strategy addresses sampling pattern, for example grid sampling (random, stratified, systematic) and/or judgemental.
Do contaminants exist in more than one phase or could the remediation process mobilise the contaminant from one phase to another?	Different pollutant linkages may exist for the same contaminant in different phases and all may need to be assessed to verify remediation.
Does the conceptual model identify off-site receptors and potential pathways?	Off-site or boundary monitoring locations may be required for surface water, groundwater or ground gas monitoring.
Will the monitoring/sampling points be useable during the entire remediation and, where necessary, development process?	Chose locations with care especially if remediation is concurrent with redevelopment. Close liaison between implementation programme manager and redevelopment designers/contractors is required to secure access to monitoring points.
Does remediation involve a moving stream (for example. soil washing, <i>ex situ</i> stabilisation and solidification)?	Soil sample locations should be from fixed points (for example a discharge point) and composite sampling may be considered, for example from specified time intervals.
Does remediation involve a static or turned pile (for example biopile, windrow turning)?	Shallow monitoring locations will not be representative of the pile. Heterogeneity is likely to be significant, but less so if the pile is regularly turned.
Does remediation involve the removal of contaminated soil?	Sampling on the base and sides of the excavation will be required to verify that the remaining soil meets remedial objectives. There should also be a requirement to sample soil used as backfill to ensure that remediation objectives are met.
Does remediation involve an active <i>in situ</i> process?	Sampling/monitoring will be required at locations within and around the remediation area as well as from locations within the reagent delivery/contaminant extraction system. Significant issues will include contaminant distribution and phase (for example the presence of NAPL), strata heterogeneity and the zone of influence of any injection or extraction system.
Does remediation involve a passive <i>in situ</i> process?	Monitoring will be required at locations within and around the contaminant plume.
Is an attenuation process located at plume fringes?	Multi-level sampling may be needed (for example Wilson <i>et al.</i> , 2004)

4.5 The number and frequency of samples or measurements

All sampling exercises have an underlying statistical population (whether or not it is explicitly acknowledged). A useful way of visualising the population is to see it as being the entire body of material (for example the total volume of soil submitted to an ex situ process, or the volume of groundwater in a contaminant plume) about which information is collected via monitoring or sampling. This helps to reinforce the importance of stating the statistical population explicitly, as the defined population clearly has a direct bearing on where and when samples are taken. It also helps to clarify precisely which aspects of the remediation strategy will be quantified by the resulting data.

The value of a statistical approach to determining the number of samples or measurements taken can be appreciated most clearly when considering how many samples should be taken to meet a particular objective. Suppose that, following remediation of a 1-hectare plot, the aim of the sampling is to test whether or not a mean concentration has been met (for a particular contaminant). Clearly just one sample would not produce a reliable conclusion. Equally, 10,000 samples spread across 1 m² squares would be almost certain to provide the "true" mean, but at enormous cost. The most appropriate number of samples therefore lies somewhere between 1 and 10,000. But where?

There is no magic number, and the monitoring/sampling effort should be consistent with the complexity of the exercise and reliability of the decision. The key issues that should be considered include:

- The remediation objectives and criteria.
- The variability of the material or substance (spatial and/or temporal).
- The reliability of the decision (bias, precision and level of confidence).

As a general rule, the more variable the population (for example the soil or groundwater to be treated), the more uncertain the conclusions will be for a given amount of sampling. The variability will therefore need to be estimated from data obtained during earlier investigations, including treatability studies. Setting the number of samples is likely to be an iterative process, with consultation among involved parties. In most cases the decision will be a compromise between cost and reliability.

The verification plan should include a full justification of the number of samples and measurements chosen with regard to variability and level of confidence in a decision. A statistical approach offers a powerful way to quantify uncertainty, and BS EN 14899:2005 provides guidance on setting the number of samples using summary statistics (mean and standard deviation). Similar guidance is available for water quality (BS EN ISO 5667 series). Several approaches exist that link the number of samples taken to confidence limits and variability, depending on the statistical parameter being measured. As remediation proceeds, estimates of variability should be challenged to assess whether the number of samples will actually achieve the stated level of confidence. INFO 4-1 also contains a list of other key references that address statistical planning for developing sampling plans.

In many cases, particularly with gas and groundwater measurement/sampling, temporal variability will need to be assessed. The frequency and duration of sampling/monitoring are therefore of equal importance to the location and number of samples and measurements.
4.6 Quality assurance/quality control

Quality assurance is an important project-specific aspect of quality management throughout the implementation of the remediation strategy. There are two key features (from CLR11):

- The need to provide an accurate and permanent record of remediation and the standard it has achieved (the verification report).
- Remediation may need maintenance and/or monitoring to achieve or demonstrate on-going effectiveness.

The verification plan should include quality assurance and quality control requirements for inspection, sampling and monitoring data that should take into account:

- Roles and responsibilities, including qualification and experience of personnel.
- Qualification, accreditation and experience of contractors and subcontractors, e.g. laboratories.
- Sampling and analysis, e.g. methods, equipment calibration.
- Quality control, e.g. duplicate sampling, trip and field blanks, etc.
- Labelling, storage and chain of custody of samples.
- Recording and storage of data (see Section 5.1.1).
- Data validation and review.
- Contingency plan.
- Reporting.

4.7 The verification plan

The verification plan should set out the requirements for gathering data to demonstrate that remediation meets the remediation objectives and criteria. CLR 11 Figure 4B Output 2 identifies that a verification plan will typically contain (Defra and Environment Agency 2004):

- Introductory information (site location, responsible parties for different activities, etc.).
- Background information (for example risk assessment findings, nature of contamination, etc.).
- The scope (objectives) of remediation to be undertaken to manage the relevant pollutant linkages identified within the conceptual model.
- Critical performance characteristics (criteria) of each element of remediation that must meet the specification for the remediation to be successful.
- For each element, how lines of evidence can be collected and how performance can be verified.
- For each element, who will be responsible for carrying out measurements or tests, and at what frequency. Reporting requirements for all data,

including consignment and waste carrier notes, analytical report sheets, quality assurance information, etc.

- For remediation where treatment may continue after the initial installation, a decision on the most appropriate time to produce the verification report.
- Proposed response actions if measured data does not conform to specification.
- Schedule of third party contacts, including those to whom verification data should be provided.
- Key criteria that must be met to allow discharge or surrender of regulatory permits or conditions.

If necessary, the verification plan should also include outline information on:

- The need for long-term monitoring (see Chapter 6).
- Communications plan developed as part of the remediation strategy.

4.7.1 Communications plan

CLR11 states that "a formal risk communication strategy will be an important element of many land contamination projects" and refers to SNIFFER (1999, and future updates²) for guidance on how to approach communication. It will usually be the responsibility of the problem-holder and their adviser (environmental consultant) to develop the communications plan, but in some cases, for example with contentious sites, other parties such as regulators may wish to be involved with or develop their own communications plan.

The need for a communications plan for verification will depend on the complexity of the site or remediation, the range of stakeholders involved, and the sensitivity of the project. Communication of verification will need to take account of stakeholders' perceptions in order to build trust, and early engagement is recommended. Any plan developed should be clearly written to ensure meaningful dialogue with all identified stakeholders, and should include:

- Objectives important to set objectives broadly based around the effective two-way transfer of information between expert and non-expert groups and increase confidence in the remediation process.
- Target stakeholders may include groups with professional, financial, environmental, political and social interests.
- Key messages to target message to specific groups, allow others to raise concerns and provide clear explanations. Perceptions of each stakeholder group may vary and information may need to be communicated, for example:
 - to show the remediation is on-track (to time, budget and/or quality).
 - to show risks to local residents are being effectively managed.
 - to mitigate the perception of blight.

² see <u>http://www.sniffer.org.uk</u> for updates

- Strategy what will be done rather than how, for example the strategy may include to communicate regularly with key stakeholders and to engage actively with the local community.
- Tools and techniques specific communications techniques to be used, for example: newsletters, press releases, "coffee morning" briefings, hotline or website. SNIFFER (1999) includes a check-list of a range of approaches that may be used.
- Activities schedule it is useful to develop a timetable of activities to ensure that information exchange is timely.

4.8 Summary

A verification plan may be developed in one or two stages, depending on timescales, costs and the complexity of the remediation design. This programme of sampling, monitoring and inspection activities is specifically aimed at gathering evidence to show that remediation objectives have been, or will be, met. It should be set out in a verification plan within a quality management framework. All identified sampling and monitoring activities must link clearly to the lines of evidence identified from the conceptual model. In some cases, where monitoring is required to satisfy long-term objectives, verification may be staged to ensure that compliance with short-term, medium-term and long-term criteria is assessed and the need for further work documented.

5 Implementation of verification

5.1 Implementation

The roles and responsibilities for data collection and management should be clearly set out and agreed with relevant parties before implementation (see Section 3.2). It is important that data are not just collected but used to review the conceptual model. This review will usually be iterative, and often set against key milestones, particularly where the performance of remedial treatment is predicted from treatability studies and/or modelling, or where the remediation is phased. The key stages of review are:

- To assess whether remedial criteria are being or have been met.
- Reviewing and updating as necessary the conceptual model to assess whether risks have been managed and objectives met.
- To agree verification with the relevant parties and confirm whether monitoring or maintenance is needed to meet long-term remediation objectives.

This review process is indicated in Figure 5.1.

5.1.1 Data recording

A fundamental requirement for verification is that complete and accurate records are prepared and maintained throughout the remediation project. The collection of data, from sampling through analysis to data storage, should follow strict protocols within established quality control/quality assurance (QA/QC) procedures. Data reporting systems are now widely available, either developed in-house, adopting an "industry standard", such as the AGS data transfer format (<u>http://www.ags.org.uk</u>), or commercially available systems using spreadsheet, data base or geographical interface system functionality. Any system selected for a particular remediation project should be fit for purpose and a number of key questions should be addressed, such as:

- What questions are the data intended to answer?
- How much data will be generated?
- How quickly are the data needed? Do they need to influence and inform the remediation work on site?
- Will the site be subdivided into zones or data released against development milestones?
- Will time-related data be generated for example from gas and groundwater monitoring programmes?
- Who will have access to the data and what are their requirements?
- What will be the best way to present the data to aid understanding?
- What sort of data outputs will be required?

Data may be available at the time of sampling (for example, weather and ground conditions, sample appearance and odour), but may be quickly lost if not recorded. A

decision needs to be made on the level of information that could be usefully recorded during sampling, monitoring and inspection activities. Most organisations use in-house pro-forma for recording sampling, monitoring and inspection data that will often include standard information as identified in Table 5.1.

Date and time	Site code/address	
Complex details		
	Remediation contractor	
Sample code	Client contact details	
Weather conditions	Sample location	
Ground conditions		
Sampling objective		
Type of material sampled	Sampling method	
Sample description	Sampling equipment	
Sampling details (for example, time start and finish, purge volumes, depth, sample size/increment/mixing)		
Health and safety measures		
List of determinands	Pre-treatment, preservation,	
Laboratory details	storage and transport details	
Deviations from verification plan	Delivery to laboratory –	
(and reasons why)	cross-reference to chain of custody form	
Received by and date	Signature of recipient	

Table 5.1Typical information on a sampling record.

Annex B of BS EN 14899:2005 provides an example of a sampling record.

5.1.2 Communicating results

It is also important that the communications plan (see Section 4.7.1) is followed to ensure efficient two-way transfer of information with the multiple stakeholder groups involved in the remediation process. The plan may have different implementation needs before during and after remediation is completed, and may include meetings, open days on site, newsletters and non-technical summaries and reports.



Figure 5.1 Implementation of verification plan.

5.2 Implementing the verification plan

Implementation of the verification plan is an iterative process that ultimately leads to a decision to cease monitoring or sampling and close the project. A suitably qualified person, identified in the verification plan, should carry out periodic review of data to answer the following questions:

- Does data meet lines of evidence requirements?
- Has each remediation criterion been met?
- Have remediation objectives been met?

These iterations will lead to progressively considering separate data streams together until it is clear that all remediation objectives have been achieved. A contingency plan should also be produced to identify the course of action to be taken if results fall outside acceptable limits, particularly where this may raise concern that the remediation is unlikely to meet its objectives. Any changes to the verification plan, particularly where they lead to a change to the objectives, need to be documented, justified and, where necessary, agreed with relevant parties.

5.2.1 Does data meet lines of evidence requirements?

Tracking the remediation process by systematic evaluation of verification data should ensure that potential difficulties in meeting remediation criteria can be identified at an early stage. Action may then be taken to review criteria, modify the remedial process or consider other options if objectives are not likely to be met. The over-riding aim is to ensure that remediation objectives are met, and this is a more likely outcome if periodic review takes place rather than wait until the end of remediation to review the verification data. Data that may lead to a review include:

- Change in environmental conditions (for example temperature, pH).
- Decline in contaminant concentrations is not as predicted (for example in a biopile).
- Contaminant plume does not shrink or stabilise as predicted during MNA or *in situ* treatment.
- Diminishing return in efficiency (for example SVE/air sparging or pump and treat).
- Change in groundwater flow or head up gradient of a slurry wall or PRB.
- Failure to prevent the migration of ground gases (for example passive venting, containment or active abstraction).

5.2.2 Have remediation criteria been met?

A positive assessment of the lines of evidence should enable the integration of linked evidence to justify and document that remediation criteria have been met, having regard to the data quality needs set out in the verification plan.

5.2.3 Have remediation objectives been met?

Finally an assessment of performance against all remediation criteria will be carried out to ensure that the remediation objectives are achieved. This may be a complex operation where criteria relate to several remediation activities, phases or timescales. The conceptual model must be reviewed, and presented in the verification report, to demonstrate whether the remediation objectives are met. When needed to satisfy long-term objectives, any long-term monitoring requirements must also be identified and documented in the verification report.

5.3 The verification report

The verification report provides a complete record of all remediation activities on site and the data collected as identified in the verification plan to support compliance with agreed remediation objectives and criteria. In the past, many remediation projects were carried our without being properly recorded. Any further work on such sites, for example redevelopment, may lead to unnecessary expenditure because of the lack, or quality, of documentation. A verification report should be sufficiently robust to satisfy the needs of the current client and regulator, and to be available as an "as-built" record for future transactions. The typical content of a verification report is provided in Figure 4B Output 5 of CLR 11. The report sections and content are reproduced in Table 5.2 with comments added to clarify data needs.

Changes to the remediation strategy or the treatment methods employed may be unavoidable, for example as a consequence of additional contamination being found during remediation, unforeseen scaling factors from laboratory to field or unexpected weather conditions. It is important that such changes are clearly documented in the verification report and linked to a review of the conceptual model and remediation objectives.

The verification report may demonstrate that all remediation objectives have been achieved or that short or intermediate term objectives are met (for example a permeable reactive barrier has been installed and commissioned). But the verification report may be interim in nature where there is a need to achieve long-term objectives (for example contaminant concentrations in groundwater beneath the source zone achieve compliance criteria). In this case, verification activities (such as sampling, modelling and the review of the conceptual model) may need to continue until all objectives are achieved.

There is also a case for interim verification reports, particularly when the remediation is linked to development. For example, interim reports could be produced for phased release of land for redevelopment in advance of the whole remediation strategy being completed.

The need for long-term monitoring will have been reviewed and documented in the verification report, stating clearly whether verification activities cease or follow the process outlined in Chapter 6.

Report section	Content	Comment
Background information	Reasons and objectives for the remediation	Any departure from original objectives must be documented
	Site details	Name, location, plan, brief history and reference to previous investigations, risk assessments and remedial actions
	Project personnel and their roles	Names, roles and contact details
Remediation	Methodology and programme	Objectives and criteria, conceptual model, remediation methods, phasing and zoning, volume and location of materials
	Verification	Lines of evidence and their integration. Monitoring and sampling methods. Communications plan.
	Emissions control and monitoring	Monitoring methods and links, where appropriate, to lines of evidence.
	Chemical and physical testing regime	Chemical and physical testing methods, QA/QC.
	On-going monitoring and maintenance	Results of monitoring and record of maintenance after remediation has been implemented.
Final site condition	Status at completion	Description of site conditions.
	Final extent of remediation	Documented assessment of data and record of decision. Revised conceptual model.
	Identification of post- treatment management needs	Monitoring and maintenance requirements. Access agreements and constraints on land use.
Third party contacts	Consultees	Contact details
	Site visits by regulators	Record of inspections and meetings. Documented agreements.
	Statutory requirements	Permit compliance (planning, waste management etc.)
	Third party agreements	Documented agreements (access rights, permit compliance)
Supporting information	Plans, as-built drawings and photographs	Photographs, plans, engineering drawings
	Test results	Field and laboratory test results
	Other documentation	Progress reports, liaison/communications log, meeting minutes

 Table 5.2 Typical content of a verification report.

The production of a verification report is integral to supporting any decision on the waste management requirements for excavation and redeposit of material, with or without treatment, in the development of land. For some specific scenarios in England and Wales this approach is described in a voluntary industry code of practice (<u>http://www.claire.co.uk</u>). Reference should be made to the relevant web sites (see Section 1.3.1) for the regulatory approach in other parts of the UK.

5.3.1 Presentation of verification data

The majority of remediation projects will generate a large quantity of data that can be difficult to present or understand in the context of the overall performance of the remediation project. The verification report should therefore present information clearly within a logical framework to demonstrate confidence in the outcome of the remediation to a range of interested parties, including regulators, site owners, funders and the local community.

Summary data can often be prepared more effectively in graphical format, including the following examples:

Time series charts: Plotting data as a time series enables trends to be visualised and compared and may allow a degree of prediction based on extrapolation of trend lines. Time series charts are particularly helpful for biological and most *in situ* remediation processes where there is a requirement to show trends in contaminant concentrations over time or mass removal of contaminants in order to demonstrate compliance with remediation criteria. Figure 5.1 shows a time-series plot for the mass recovery rate of hydrocarbons from fractured sandstone during multi-phase extraction as part of a remediation strategy. The strategy included: hydrocarbon recovery to asymptotic conditions (beyond which recovery would not be cost or energy-efficient), contaminant rebound monitoring, and measurement of geochemical indicators to assess whether natural attenuation is viable following hydrocarbon recovery.



Figure 5.1 Time-series plot showing hydrocarbon mass recovery rate from a multi-phase extraction project³.

³ The Environment Agency acknowledges CELTIC and Environment Agency Wales for providing this figure

Spatial plots: The use of spatial plots may enhance the presentation of data, for example to show the distribution of residual soil contamination, or the spatial extent of a groundwater plume with time, for example during monitored natural attenuation or comparing pre-remediation and post-remediation conditions. Figure 5.2 shows the distribution of a methyl tertiary butyl ether (MTBE) plume monitored during natural attenuation over a period of over two years.



Figure 5.2 Natural attenuation of a MTBE plume.

As built engineering drawings: As built engineering drawings will provide a valuable record of the physical dimensions of any engineered structures and location of monitoring infrastructure associated with remediation. This is particularly important where access may be needed for a long time period, for example for maintenance, or there is a need to ensure that long-term remediation criteria are achieved. Examples may include containment systems, showing the location and depth of bentonite slurry walls, or the spatial extent and depth of a cover system, a permeable reactive barrier (PRB), landfill gas abstraction system or pump-and-treat system. As-built drawings can also be used to identify where remediation has been carried out including the treatment area and location of any deposited soil – either untreated, treated or imported to site.

Figure 5.3 shows a location plan for a PRB system at a former gasworks site that includes:

- A bentonite slurry wall to capture the contaminant plume and prevent offsite migration.
- A PRB to treat contaminants in the groundwater plume using aerated sand chambers and granular activated carbon.
- Research soil mix columns to test a complementary (source or plume) treatment option.



Figure 5.3 As-built drawing showing a permeable reactive barrier⁴.

Statistical analysis of verification data: The presentation options for data will depend on the statistical test used but a wide range of presentation formats is readily available to help present complex data in a visually clear way. To assist selection, the USEPA has published an excellent "tool-box" of useful techniques that can be used to assess and present environmental data (USEPA, 2006a) together with guidance on data quality assessment (USEPA, 2006b). Figure 5.4 shows contaminant concentration statistics before and after remediation using a box plot. This shows the range of maximum and minimum values (blue diamonds), mean (red cross) and 95 percentile (upper bar at around 4 in the pre-treatment plot). In both plots the maximum value is treated as an outlier.

⁴ The Environment Agency acknowledges National Grid Property Holding and Department for Trade and Industry (DTI) for providing this drawing



Figure 5.4 Box-and-whisker plot of carbon disulphide concentrations⁵.

Whilst the use of summary data tables and graphical presentations can assist greatly in communicating the performance of remedial activities, these should always be backed up by the inclusion of fully comprehensive data (see Section 5.3) within the verification report.

5.4 Summary

After this stage the verification plan will have been implemented and data periodically reviewed to ensure that remediation objectives have been or can be met. Any necessary changes to the verification plan will have been justified and agreed with all relevant parties. The implementation of verification is an iterative part of the remediation strategy and not an 'end-of-treatment' process.

The key output from implementation is the verification report that may need to be presented to a wide range of interested parties. It is important that the decision of whether remediation objectives have been met should be clearly stated.

Verification may be staged to take account of time-dependent objectives and criteria. Any recommendations for monitoring and maintenance, linked to specific long-term objectives or criteria that remain, must also be clearly stated in the verification report.

⁵ The Environment Agency acknowledges Arcadis GMI and Akzo Nobel UK Ltd. for providing this figure.

6 Long-term monitoring and maintenance

6.1 Introduction

It is often the landowners wish for remediation strategies to be designed to limit the need for long term monitoring and/or maintenance. In such cases, where the verification has adequately demonstrated that all the remediation objectives have been met, a verification report (see Section 5.3) can be prepared without the need for an on-going programme of monitoring and/or maintenance.

However, on some sites, long-term monitoring and maintenance may be required as part of the original remediation strategy to determine the long-term effectiveness of some measures (for example, for a containment system, landfill gas abstraction or a permeable reactive barrier). This clearly involves on-going costs and access requirements that need to be factored into the overall budget for the remediation project. Alternatively, it is possible that the need for such an on-going programme, although not anticipated in the original strategy, becomes apparent during verification. In all cases, monitoring requirements should relate to long-term criteria that need to be achieved to pre-defined timescales (see Section 3.3.2). This is particularly important where redevelopment could be blighted by "open-ended" monitoring timescales or unclear remediation end-points.

Where on-going monitoring and maintenance are required to verify that all remediation objectives are met, such a programme must be defined in a monitoring and maintenance plan that describes:

- The scope and context of the monitoring and maintenance activities, including the remediation objectives and criteria that have yet to be achieved.
- The detailed specification of the work.
- The roles and responsibilities for carrying the work out.
- The locations, frequency and duration of monitoring.
- The detail of analyses to be performed (analytical suite, limits of detection, etc).
- The criteria for data evaluation, including when monitoring can cease.
- The proposals for review of monitoring and maintenance activities.
- The mechanics and format for recording, collating and reporting data.
- Contingency plan detailing a sequence of response actions if remediation criteria are not, or are not likely to be, met.
- The mechanism for making decisions about exceptional activities, for example replacement or repair, and communication with involved parties.

Monitoring or maintenance should continue until you can demonstrate that all the remediation objectives have been met, that is when the pollutant linkages have been

permanently broken and any harm or pollution caused has been mitigated. Figure 6.1 summarises the proposed steps for long-term monitoring and maintenance.



Figure 6.1 Flow chart for long-term monitoring.

6.2 Produce the monitoring and maintenance plan

The potential need for a monitoring and maintenance plan will have been established initially during the development of the remediation strategy (Section 4.3.5), and confirmed during implementation (Section 5.3).

6.2.1 Monitoring activities

Long-term monitoring should be carried out in accordance with the monitoring and maintenance plan that is reviewed periodically to ensure that the scope of work is still valid. Typical issues that may need to be managed include:

- Competence of monitoring personnel.
- Monitoring schedule.
- Integration of specialist contractors (for example geophysical survey and water sampling, ensuring monitoring and maintenance schedules do not conflict).
- Access rights.
- Contingency plan with clearly defined response actions in the event that monitoring criteria are exceeded.
- Review, reporting and communication responsibilities.
- Agreeing and documenting significant changes.

The contingency plan is an important part of the monitoring and maintenance plan to ensure that data collection remains effective throughout the monitoring period. It is good practice to set out the potential response actions in a contingency plan that identifies a sequence of actions that escalate when criteria are still not met. For example, a sequence of typical response actions could be:

- 1. To validate the measured data.
- 2. To obtain more data (for example an additional sampling exercise or collection of supporting data).
- 3. To determine the nature and extent of the problem areas by further specific site investigation and monitoring (on an increased frequency and a tighter grid of locations).
- 4. To revise the conceptual model and carry out a detailed quantitative risk assessment using all available data.
- 5. To determine the need for and scope of additional remediation action (modifications of existing or new technique).
- 6. Implementation and verification of such remediation.

The reasons or trigger for invoking response action must be clearly set out in the plan and agreed with/communicated to all involved parties.

6.2.2 Maintenance activities

The long-term maintenance activities will depend on both the nature of monitoring carried out and the remediation technology being used. The need for and scope of any maintenance activities will be identified in the remediation strategy, but is likely to be defined post remediation when the detailed long-term monitoring and maintenance plan is finalised.

The objective of maintenance is to ensure that the remediation and monitoring infrastructure continue to function and operate as designed. Activities may include:

Monitoring infrastructure	Remediation infrastructure
Inspection of monitoring boreholes	Inspection (such as abstraction wells, pipework, pumps, surface condition of cover system)
Servicing of equipment, such as sampling pumps	Servicing of equipment, such as pumps, and replacement of consumables, such as filters
Replacement or rehabilitation of monitoring boreholes	Rehabilitation (such as replacement of reactive material in a PRB, repair of a cover system, replacement of pumps, abstraction wells and pipework, etc.)

The activities should be reviewed as circumstances can change in the long-term, for example in response to an increased frequency, severity or extent of flooding, more severe drought conditions, colder winters, or secondary sources that may cause recontamination of soil (Clark *et al.*, 2008, Douay *et al.*, 2008), surface water or groundwater. Maintenance activities must be recorded and reported to relevant stakeholders in accordance with provisions agreed in the monitoring and maintenance plan.

6.3 Identify and procure services

Reference should be made to CLR11 for further information on procurement and management issues.

6.4 Implementation of the monitoring and maintenance plan

6.4.1 Review of monitoring results and decision to cease monitoring

The monitoring results will need to be routinely reviewed against the monitoring objectives and criteria. The results should be reported and provided to appropriate parties at a pre-agreed frequency, with a review to determine whether:

• Monitoring objectives and criteria have been achieved.

- The monitoring and maintenance plan is still valid.
- There is a need for further monitoring and maintenance.

Once objectives and criteria have been achieved a monitoring and maintenance report should be prepared and lodged with all appropriate parties for agreement. This report will be used to document the achievement of all remediation objectives and should include a revised conceptual model

6.5 The monitoring and maintenance report

Monitoring and maintenance reports will take the form of interim progress reports and a final report to show that all objectives and criteria have been achieved. A typical monitoring and maintenance report should include sections that deal with (Figure 4C OUTPUT 1 and 2 of CLR 11):

- Maintenance
 - Scope of the work covered by the report
 - Schedule of regular activities since the previous report
 - Report on exceptional work items carried out since previous report
 - Information on use of consumables, energy etc.
 - Requirement to action repairs or service plant
 - Recommendations for future routine or exceptional work items
- Monitoring
 - Scope of the work covered by the report
 - Schedule of regular activities since the previous report
 - Report on visual inspection, monitoring and test results, including exceptional results recorded since the previous report
 - Assessment of compliance against previously agreed criteria
 - Report on any actions taken in response to exceptional results
 - Recommendations for future monitoring and any variations to the agreed monitoring programme
 - Supporting information, including sampling, analytical and quality assurance procedures used, type of equipment, calibration records, location and construction of monitoring points.

6.6 Summary

The United States Environmental Protection Agency published the proceedings of a conference on improving long-term monitoring and remedial performance (USEPA 2000b). It discusses approaches to reduce costs and increase confidence, illustrated by a number of case studies, and highlights the need for novel, cost-effective monitoring technologies and regulatory acceptance of the results.

Regulatory acceptance can be eased by having transparent decision-making through design and implementation of the remediation strategy and agreement of remediation objectives, including, where necessary, predicted end-points. The need for long-term monitoring can then be agreed at an early stage in the development of the remediation strategy and confirmed during implementation.

After this stage a number of routine monitoring reports will have been produced, detailing the monitoring and maintenance activities carried out, an assessment of the results, and recommendations for further action. Ultimately all remediation objectives will have been met and a final report will include a review of the conceptual model and the documented decision to cease monitoring. These reports should be lodged with the verification report to provide a complete and final record of verification activities.

7 Confidence through verification

This document provides a framework for verification of remediation that equally applies to traditional civil engineering approaches and both 'passive' and 'active' biological, chemical, physical and thermal process-based technologies. It recommends that the conceptual model is reviewed throughout the risk management stages and that lines of evidence are developed for remedial activities to increase confidence in the outcome of a remediation strategy. Communication of the findings is potentially important as a wide range of parties may have an interest in the outcomes.

This document highlights the need to have a range of tools to deliver confidence in the outcome of remediation to a wide range of interested parties. The verification approach must be knowledge-based, with the following used in an iterative review of the conceptual model:

- Knowledge of remediation processes, their operating windows, and scaling factors between laboratory and field trials.
- Knowledge of sampling approaches that may be used to evaluate compliance with remediation criteria to an appropriate level of confidence.
- Knowledge of monitoring techniques that can be used to meet data quality requirements.
- Knowledge of methods to assess data collected to satisfy lines of evidence.
- Knowledge of methods that can be used to support decision-making.

While the UK can boast an extensive and innovative research portfolio to meet current and future environmental challenges, exploitation can be significantly delayed without high quality field demonstration and dissemination to turn innovative research approaches into commercially accepted options. A number of initiatives have been established in the UK and overseas to fund research and promote technology transfer from academia or other innovators to problem-holders. Brief details of some of the more important web-based resources are provided in INFO 4-2.

Such initiatives should improve dissemination of knowledge on existing technologies and create a climate that is more responsive to the uptake of new technologies, and ultimately lead to improved confidence and societal acceptance of knowledge based risk management technologies.

This document encourages the collection and integration of multiple lines of evidence to support the verification of remediation objectives. Current methods used to perform such integration mainly rely on professional judgement, but other logic and relationshipbased approaches are used including:

- The use of authoritative guidance.
- Correlation of remediation operating parameters with risk (contaminant) reduction, using laboratory treatability studies and field pilot studies.
- Indexing a number of lines of evidence to represent them collectively as a single parameter (for example Dawson *et al.*, 2007).
- Modelling the impact of remediation on contaminant concentration and distribution.

As long-term and global drivers, such as ecosystem function (Burger, 2008) and climate change adaptation and mitigation respectively, are increasingly influencing environmental decision making, more sophisticated decision support tools are being used to help evaluate the importance of issues and justify and communicate a decision (Linkov *et al.*, 2009). Approaches are likely to evolve and incorporate multi-criteria analysis and statistical methods to facilitate the integration of multiple information sources. As approaches develop they may potentially provide more opportunity to truly integrate the data from multiple lines of evidence in the decision making process for the remediation of land contamination.

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Glossary

Conceptual model - a simplified representation of how the real system is believed to behave based on qualitative analysis of field data. A quantitative conceptual model includes preliminary calculations for key processes.

Data quality – the totality of features and characteristics of data that bear on its ability to meet the stated or implied needs and expectations of the customer.

Data quality objectives – qualitative and quantitative statements that define the type, quality and quantity of data necessary to support decision-making.

Effective data – data of known quality that can be logically shown to be effective for making defensible project decisions because both sampling and analytical uncertainties have been managed to meet clearly defined project objectives.

Implementation plan – a plan that sets out all aspects of design, preparation, implementation, verification, long-term maintenance and monitoring of the remediation.

Line of evidence –collection of data sets for key parameters that support agreed remediation criteria to demonstrate the performance of remediation.

Long-term monitoring – monitoring following the construction and commissioning of some active, passive or containment remediation measure that is used to measure compliance with long-term remediation objectives over a period of years to decades.

Population – a statistical term for defining the total volume of material about which information is required through sampling.

Remediation – action taken to prevent or minimise, or remedy or mitigate the effects of any identified unacceptable risks.

Remediation criteria – measures (usually, but not necessarily, expressed in quantitative terms) against which compliance with remediation objectives will be assessed.

Remediation objective – a site-specific objective that relates solely to the reduction or control of risks associated with one or more pollutant linkage.

Remediation strategy – a plan that involves one or more remediation option to reduce or control the risks from all the relevant pollutant linkages associated with the site.

Validation – the process by which a sample, treatment method, or data are deemed to be suitable for a specified process. Validation can be based on a theoretical understanding of a process, a literature review of previous use, or determined on-site

Verification – the process of demonstrating that the risk has been reduced to meet remediation criteria and objectives based on a quantitative assessment of remediation performance

Verification plan – a plan that sets out the requirements for gathering data to demonstrate that remediation meets the remediation objectives and criteria.

Verification report – provides a complete record of all remediation activities on site and the data collected as identified in the verification plan to support compliance with agreed remediation objectives and criteria.

Appendix A - Information map

This section provides information on key publications that contain more detailed technical information pertinent to the verification process.



INFO 2-1	DEVELOP A MONITORING/SAMPLING PLAN
BSI 2005	BS EN 14899: Characterization of waste – Sampling of waste materials – Framework for the preparation and application of a Sampling Plan.
	This European Standard provides a framework that should be used to design and develop a sampling plan. It addresses sampling activities and the development of a sampling report, and is supported by the following five technical reports
	PD CEN/TR 15310-1:2006. Characterization of waste - Sampling of waste materials – Part 1: Guidance on selection and application of criteria for sampling under various conditions.
	PD CEN/TR 15310-2:2006. Characterization of waste - Sampling of waste materials – Part 2: Guidance on sampling techniques.
	PD CEN/TR 15310-3:2006. Characterization of waste - Sampling of waste materials – Part 3: Guidance on procedures for sub-sampling in the field.
	PD CEN/TR 15310-4:2006 Characterization of waste - Sampling of waste materials – Part 4: Guidance on procedures for sample packing, storage, preservation, transport and delivery.
	PD CEN/TR 15310-5:2006. Characterization of waste - Sampling of waste materials – Part 5: Guidance on the process of defining a sampling plan.
BSI 2006	BS EN ISO 5667 consists of twenty parts, under the general title <i>Water quality</i> — <i>Sampling</i> :
	Part 1 - Guidance on the design of sampling programmes and sampling techniques - sets out the general principles for, and provides guidance on, the design of sampling programmes and sampling techniques for all aspects of sampling of water (including waste waters, sludges, effluents and bottom deposits).
BSI 2002	BS ISO 10381 consists of six parts, under the general title <i>Soil quality</i> — <i>Sampling</i> :
	Part 1 - Guidance on the design of sampling programmes - sets out the general principles to be applied in the design of sampling programmes for the purpose of characterising and controlling soil quality and identifying sources and effects of contamination of soil and related material
BSI 2007	BS ISO 18589-2 Measurement of radioactivity in the environment – soil.
	Part 2: Guidance for the selection of the sampling strategy, sampling and pre-treatment of samples.
	This part of ISO 18589 specifies the general requirements for planning (desk study and area reconnaissance) sampling and the preparation of samples for testing. It includes the selection of the sampling strategy, the outline of the sampling plan, the presentation of general sampling methods and equipment, and the methodology of the pre-treatment of samples.
BSI 2008	BS ISO 18772 Soil quality – Guidance on leaching procedures for subsequent chemical and ecotoxicological testing of soils and soil materials.
	This standard provides guidance on the appropriate use of leaching tests on soils and soil materials in order to determine the leaching behaviour in a risk management context.

INFO 3-1	IDENTIFY VERIFICATION NEEDS FOR A REMEDIATION STRATEGY
EA 2001	Guide to good practice for the development of conceptual models and the selection and application of mathematical models of contaminant transport processes in the subsurface.
	http://publications.environment-agency.gov.uk/pdf/SCHO0701BITR-e-e.pdf
	This document describes an approach to contaminant fate and transport modelling in the sub-surface, from setting objectives to interpretation of results. It highlights the issues that need to be considered and signposts to key references.
Eurachem 2007	Measurement uncertainty arising from sampling: a guide to methods and approaches. Eurachem. ISBN 978 0 948926 26 6.
	http://www.eurachem.org/guides/UfS_2007.pdf
	This document provides guidance on empirical and modelled approaches that can be used to measure the uncertainty of measurements. It covers the whole measurement process and describes the errors that contribute to total measurement uncertainty.
USEPA 2000	Guidance for the data quality objectives process. EPA QA/G-4.
	http://www.epa.gov/quality/qs-docs/g4-final.pdf
	This document provides guidance on a systematic planning process for environmental data collection.
USEPA 2000	Data quality objectives process for hazardous waste site investigations. EPA QA/G-4HW. <u>http://www.epa.gov/quality1/qs-docs/g4hw-final.pdf</u>
	This document provides guidance on applying the DQO process to hazardous waste site investigations. (Note in the US, this includes contaminated land)
USEPA 2001	Current perspectives in site remediation and monitoring: Applying the concept of effective data to environmental analyses for contaminated sites. EPA 542-R-01-013.
	http://www.cluin.org/tiopersp
	This is an issues paper that discusses uncertainty around the use of contaminant data produced by analytical chemistry methods. In particular it addresses the need for effective data for making specific decisions.

INFO 3-2	LINES OF EVIDENCE: TREATABILITY STUDIES
USEPA 1989	Treatability studies under CERCLA: an overview. Publication No. 9380.3-02FS
	http://www.epa.gov/superfund/resources/remedy/pdf/93-80302fs-s.pdf
	This fact sheet summarises the information required to plan and carry out a treatability study to support the selection, design and implementation of a remediation technology.
USEPA 1992	Guidance for conducting treatability studies under CERCLA. EPA/540/R- 92/071a.
	http://www.epa.gov/superfund/resources/remedy/pdf/540r-92071a-s.pdf
	This document focuses on treatability studies conducted in support of remedy screening/selection and implementation. An 11 step generic protocol is included. A number of technology specific guidance documents are published (below).
USEPA 1991	Guide for conducting treatability studies under CERCLA – aerobic biodegradation remedy screening. EPA/540 2-91 013A
	http://www.epa.gov/superfund/resources/remedy/pdf/5402-91013a-s.pdf
USEPA 1991	Guide for conducting treatability studies under CERCLA: soil vapour extraction. EPA/540/2-91/019A. Office of Emergency and Remedial Response.
	http://www.epa.gov/superfund/resources/remedy/pdf/5402-91019a-s.pdf
USEPA 1991	Guide for conducting treatability studies under CERCLA: soil washing. EPA/540/2-91/020A. Office of Emergency and Remedial Response.
	http://www.epa.gov/superfund/resources/remedy/pdf/5402-91020a-s.pdf
USEPA 1992	Guide for conducting treatability studies under CERCLA – chemical dehalogenation. EPA/540/R-92/013a
	http://www.epa.gov/superfund/resources/remedy/pdf/540r-92013a-s.pdf
USEPA 1992	Guide for conducting treatability studies under CERCLA: solvent extraction. EPA/540/2-92/016a. Office of Emergency and Remedial Response.
	http://www.epa.gov/superfund/resources/remedy/pdf/540r-92016a-s.pdf
USEPA 1992	Guide for conducting treatability studies under CERCLA: thermal desorption. EPA/540/2-91/074A. Office of Research and Development, Washington D.C.
USEPA 1993	Guide for conducting treatability studies under CERCLA – biodegradation remedy selection. EPA/540/R-93 519a
	http://www.epa.gov/superfund/resources/remedy/pdf/540r-93519a-s.pdf
USACE 1995	Treatability studies for solidification/stabilization of contaminated material. US Army Corps of Engineers Technical Letter No. 1110-1-158.
	http://www.wbdg.org/ccb/ARMYCOE/COETEK/tl1_158.pdf
	This letter furnishes information and guidance on scoping a treatability study for solidification/stabilisation (S/S) of contaminated material.
EA 2002	Laboratory to field scale relationships in the assessment of the potential for monitored natural attenuation of contaminants in groundwater. R&D

	Technical Report P2-245/TR Environment Agency Bristol
	http://publications.environment-agency.gov.uk/pdf/SP2-245-TR-e-p.pdf
	This report discusses the interpretation of laboratory data for field applications of monitored natural attenuation to dissolves contaminants in groundwater. It serves as a reminder that site specific data will (almost) always be needed to assess a site and to highlight the difficulties of using laboratory data beyond its original purpose.
EA 2000	Guidance on the assessment and monitoring of natural attenuation of contaminants in groundwater. R & D Publication 95.
	http://publications.environment-agency.gov.uk/pdf/SR-DPUB95-e-e.pdf
	This report provides guidance on the assessment of monitored natural attenuation in any given situation and comprises: screening procedures to assess the viability of natural attenuation, procedures to demonstrate current attenuation properties, procedures to evaluate longer term attenuation capability and procedures to verify attainment of the agreed remedial objectives
EA 2002	Guidance on the use of permeable reactive barriers for remediating contaminated groundwater. National Groundwater and Contaminated Land Centre Report NC/01/51.
	http://publications.environment-agency.gov.uk/pdf/SCHO0902BITM-e-e.pdf
	This report provides guidance on the design, construction, operation and monitoring of permeable reactive barriers (PRBs). It has been prepared for Agency staff assessing third party proposals where a PRB forms part of a remedial strategy, and for problem holders.
EA 2004	Guidance on the use of stabilisation/solidification for the treatment of contaminated soil. Science Report SC980003/SR1.
	http://publications.environment-agency.gov.uk/pdf/SCHO0904BIFO-e-e.pdf
	This report provides guidance on stabilisation/solidification techniques to private and public sector organisations involved in the decision-making process for land contamination risk management and waste treatment
USEPA 2002	NATO/CCMS Pilot Study. Evaluation of demonstrated and emerging technologies for the treatment of contaminated land and groundwater (Phase III). 2001 Special Session – Performance verification of in situ remediation technologies. EPA 542-R-02-002.
	http://www.clu-in.org/download/partner/finalnato99.pdf
INFO 4-1	MONITORING AND SAMPLING APPROACH
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BSI 2001	BS 10175 Investigation of potentially contaminated sites. Code of Practice. British Standards Institution.
	This document contains technical advice on the design and implementation of site characterisation (including intrusive site investigation) activities for land contamination. It focuses on the selection and use of different field sampling and monitoring techniques, collection, handling and transport of samples, and reporting of field observations and related data
BSI 2005	BS EN 14899:2005 Characterization of waste. Sampling of waste materials. Framework for the preparation and application of a sampling plan. British Standards Institution.
	This document provides guidance on setting the number of samples using summary statistics (mean and standard deviation).
EA 2000	Technical aspects of site investigation in relation to land contamination (2 volumes). Technical Report P5-065/TR.
	Vol I http://publications.environment-agency.gov.uk/pdf/SP5-065-TR-e-e.pdf
	Vol II <u>http://publications.environment-agency.gov.uk/pdf/SP5-065-TR1-e-e.pdf</u>
	Guidance on technical site investigation issues for contaminated land is presented in two volumes. The report contains a good practice overview and aspects ranging from site records and data management to health and safety and checklists for working on operational sites.
EA 2001	Secondary model procedures for the development of appropriate soil sampling strategies for land contamination. R&D Technical Report P5-066/TR.
	http://publications.environment-agency.gov.uk/pdf/SP5-066-TR-e-e.pdf
	This report provides guidance on technical principles and procedures in designing appropriate soil sampling strategies for projects on contaminated land is presented. The report describes the secondary model procedures that form part of a hierarchy of documents providing a systematic approach to the management of contaminated land.
CIRIA 2007	Assessing risks posed by hazardous ground gases to buildings (revised) (C665). ISBN 978-0-86017-665-7.
	This report provides guidance on good practice in site investigation, collection of relevant data and monitoring programmes for a risk-based approach to land contaminated by ground gases.
CIRIA 2009	The VOC Handbook (C682). ISBN 978-0-86017-682-2.
	This report provides guidance on the investigation, assessment and management of risks associated with VOCs at land affected by contamination. It complements CIRIA C665.
USEPA 2002	Guidance on choosing a sampling design for environmental data collection. EPA/240/R-02/005. Office of Environmental Information, Washington D.C.
	http://www.epa.gov/quality/qs-docs/g5s-final.pdf
	This report provides guidance on designing statistically-based sampling schemes. It describes several basic and innovative sampling designs, and describes the process for deciding which design is right for a particular

	project.
USEPA 1996	An overview of methods for evaluating the attainment of cleanup standards for soils, solid media, and groundwater, EPA volumes 1, 2 and 3. EPA
	http://www.clu-in.org/download/stats/overview.pdf
	Provides an overview of three comprehensive volumes (below) that describe and illustrate how to use statistical tests to evaluate the attainment of cleanup standards for soil, solid media and groundwater.
	USEPA 1989. Methods for evaluating the attainment of cleanup standards. Volume 1: soils and solid media. EPA 230/02-89-042. <u>http://www.clu-in.org/download/stats/vol1soils.pdf</u>
	USEPA 1991. A guide: Methods for evaluating the attainment of cleanup standards. Volume 1: soils and solid media. EPA 9355.4-04FS.
	USEPA 1992. Methods for evaluating the attainment of cleanup standards. Volume 2: ground water. EPA 230-R-92-014.
	http://www.clu-in.org/download/stats/vol2gw.pdf
	USEPA 1994. Methods for evaluating the attainment of cleanup standards. Volume 3: reference-based standards for soil and solid media. EPA 230-R- 94-004.
	http://www.clu-in.org/download/stats/vol3-refbased.pdf
USEPA 1995	EPA Observational Economy Series. Volume 1: composite sampling. EPA-230-R-95-005.
	http://www.clu-in.org/download/stats/composite.pdf
	This report provides guidance on the selection of a composite sampling strategy to reduce the analytical costs whilst maintaining a level of uncertainty.
USEPA 1995	EPA Observational Economy Series. Volume 2: ranked set sampling. EPA-230-R-95-006.
	http://www.clu-in.org/download/stats/rankedset.pdf
	This report introduces the concept of ranked set sampling and provides guidance on its use as an alternative to simple random sampling.

INFO 4-2	REMEDIATION TECHNOLOGIES – GUIDANCE				
	Generic				
CIRIA	HARRIS, M.R., HERBERT, S.M. and SMITH, M.A. 1996. Remedial Treatment for Contaminated Land, Volume VII: Ex-Situ Remedial Methods for Soils, Sludges and Sediments Special Publication 107.				
	HARRIS, M.R., HERBERT, S.M. and SMITH, M.A. 1995. Remedial Treatment for Contaminated Land, Volume VIII: Ex-Situ Remedial Methods for Contaminated Groundwater and other Liquids. Special Publication 108.				
	HARRIS, M.R., HERBERT, S.M. and SMITH, M.A. 1995. Remedial Treatment for Contaminated Land, Volume IX: In-Situ Methods of Remediation Special Publication 109.				
CRC Lewis 1997	Suthersan, S.S. 1997. Remediation Engineering – Design Concepts. CRC Lewis Publishers, Boca, Raton, USA.				
EA 2002	EA, 2002, Source treatment of dense non-aqueous phase liquids. R&D Technical Report P5-051. Environment Agency, Bristol.				
Engineering Systems					
CIRIA	1996. Barriers, Liners and Cover Systems for Containment and Control of Land Contamination, Special Publication SP124				
	HARRIS, M.R., HERBERT, S.M. and SMITH, M.A. 1995. Remedial Treatment for Contaminated Land, Volume V: Excavation and Disposal Special Publication 105, CIRIA, London				
	HARRIS, M.R., HERBERT, S.M. and SMITH, M.A. 1995. Remedial Treatment for Contaminated Land, Volume VI: Containment and Hydraulic Measures Special Publication 106, CIRIA, London				
BRE 1994	Slurry Walls to Contain Contamination. Building Research Establishment BRE Digest 395, Garston.				
	Monitored Natural Attenuation				
EA 2000	Guidance on the assessment and monitoring of natural attenuation of contaminants in groundwater. R & D Publication 95. Environment Agency, Bristol.				
EA 1999	Natural attenuation of petroleum hydrocarbon and chlorinated solvents in groundwater R&D Technical Report P305. Environment Agency, Bristol.				
	Ex situ Bioremediation				
Battelle 1996	Biopile Design and Construction Manual. Technical Memorandum TM-2189-				
EA 2001	Remedial Treatment Action Data Sheets. Version 1. - Biopiles - Windrow Turning - Landfarming National Groundwater & Contaminated Land Centre Report NC/00/04/01.				
	Phytoremediation				
ITRC 2009	Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised. Technical/Regulatory Guidance. Interstate Technology and Regulatory Council. Available at <u>http://www.itrcweb.org</u>				

	In situ Bioremediation				
ITRC 2002	A Systematic Approach to In Situ Bioremediation in Groundwater Including Decision Trees on In Situ Bioremediation for Nitrates, Carbon Tetrachloride, and Perchlorate. Technical/Regulatory Guidance. Interstate Technology and Regulatory Council. Available at <u>http://www.itrcweb.org</u>				
GWRTAC 1996	Miller, R.R. Bioslurping. Technology Overview Report TO-96-05. Ground- Water Remediation Technologies Analysis Center. Available at: <u>http://www.gwrtac.org</u> .				
CRC Lewis 1997	Leeson, A. & Hinchee, R.E. 1997. Soil Bioventing: Principles and Practice. CRC Lewis Publishers, London.				
	Suthersan, S.S. 1997. Remediation Engineering – Design Concepts. CRC Lewis Publishers, Boca, Raton, USA.				
EA 2001	Remedial Treatment Action Data Sheets. Version 1. - Bioventing National Groundwater & Contaminated Land Centre Report NC/00/04/01.				
	Chemical Methods				
ITRC 2005	Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater (2nd edition). Interstate Technology and Regulatory Council. Available at <u>http://www.itrcweb.org</u>				
Permeable Reactive Barrier					
EA 2002	Guidance on the use of permeable reactive barriers for remediating contaminated groundwater. National Groundwater & Contaminated Land Report NC/01/51.				
Soil Washing					
CL:AIRE 2007	Understanding Soil Washing. Technical Bulletin TB 13				
JHM 2008	DERMONT, G., BERGERON, M.,. MERCIER, G. AND RICHER- LAFLÈCHE, M. 2008. Soil washing for metal removal: a review of physical/chemical technologies and field applications. Journal of Hazardous Materials 152, 1-31.				
	<i>In situ</i> Flushing				
GWRTAC 1996	Jafvert, C.T. 1996. Surfactants/Cosolvents. Technology Evaluation Report TE-96-02. Ground-Water Remediation Technologies Analysis Center. http://www.gwrtac.org				
Soil Vapour Extraction					
USEPA	PA 1996. Engineering Forum Issue Paper: Soil Vapor Extraction Implementation Experiences. Office of Solid Waste and Emergency Response. EPA 540/F-95/030				
	1997. Analysis of Selected Enhancements for Soil Vapor Extraction. Office of Solid Waste and Emergency Response. EPA-542-R-97-007				
	Air Sparging				
GWRTAC 1996	Miller, R.R. 1996. Air Sparging. Technology Overview Report TO-96-04. Ground-Water Remediation Technologies Analysis Center. <u>http://www.gwrtac.org</u>				
Multi phase extraction					
USEPA 1999	Multi-Phase Extraction: State-of-the-Practice. Office of Solid Waste and				

	Emergency Response. EPA 542-R-99-004.				
	In Situ Thermal Methods				
USEPA 1998	Steam Injection for Soil and Aquifer Remediation. EPA/540/S-97/505. Technology Innovation Office, Washington, DC				
	Thermal Desorption				
USEPA 1997	Engineering Forum Issue Paper: Thermal Desorption Implementation Issues. Office of Solid Waste and Emergency Response. EPA 540/F- 95/031.				
	Stabilisation/Solidification				
EA 2004	Guidance on the use of stabilisation/solidification for the treatment of contaminated soil. Science Report SC980003/SR1. Environment Agency, Bristol.				
	Review of scientific literature on the use of stabilisation/solidification for the treatment of contaminated soil, solid waste and sludges. Science Report SC980003/SR2. Environment Agency, Bristol.				
	Electrokinetics				
GWRTAC 1997	Van Cauwenberghe, L. Electrokinetics. Technology Overview Report TO-97- 03. Ground-Water Remediation Technologies Analysis Center. <u>http://www.gwrtac.org</u>				
Technology Demonstration and Case Studies					
CL:AIRE	Contaminated Land: Applications in Real Environments provides research bulletins and technology demonstration reports for remedial treatment technologies on contaminated sites. <u>http://www.claire.co.uk</u>				
CIRIA	CIRIA industry-focused research and guidance on construction related issues including land contamination. Publications include project reports and short case studies. <u>http://www.ciria.org.uk/</u> .				
KTN	A number of knowledge transfer networks (KTN) have been set up by the Technology Strategy Board in the UK to help disseminate and transfer knowledge to individuals, industry and other networks. Information on and access to the KTN sites can be found at: http://www.ktnetworks.co.uk/epicentric_portal/site/KTN/?mode=2				
EUGRIS	The EUGRIS portal (European Groundwater and Contaminated Land Remediation Information System) is a web-based information platform for contaminated land and groundwater. It is designed to direct users to the most appropriate sources via network and national links. <u>http://www.eugris.info</u>				
EURODEMO	EURODEMO (European Co-ordination Action for Demonstration of Efficient Soil and Groundwater Remediation) holds a database of European remediation technology demonstrations. <u>http://www.eurodemo.info/</u>				
NICOLE	NICOLE is a contaminated land management forum for the exchange of knowledge of sustainable technologies. <u>http://www.nicole.org/</u> .				
USEPA	The US Environmental Protection Agency provides information on monitoring and remediation technologies, including guidance and case studies published by the EPA and others. Available from <u>http://www.cluin-org/</u> .				
	The Triad Central web pages (<u>http://www.triadcentral.org</u>) provides general information on the Triad sampling approach and numerous case studies				

	using field measurement technologies.
FRTR	The Federal Remediation Technologies Roundtable provides information including guidance and a technologies screening matrix for the remediation of contaminated sites. Available from http://www.frtr.gov/

INFO 6-1	LONG-TERM MONITORING
EA 2000	Guidance on the assessment and monitoring of natural attenuation of contaminants in groundwater. Environment Agency R & D Publication 95.
	http://publications.environment-agency.gov.uk/pdf/SR-DPUB95-e-e.pdf
	This report provides guidance on the assessment of monitored natural attenuation in any given situation and comprises: screening procedures to assess the viability of natural attenuation, procedures to demonstrate current attenuation properties, procedures to evaluate longer term attenuation capability and procedures to verify attainment of the agreed remedial objectives
EA 2002	Guidance on the use of permeable reactive barriers for remediating contaminated groundwater. National Groundwater & Contaminated Land Report NC/01/51.
	http://publications.environment-agency.gov.uk/pdf/SCHO0902BITM-e-e.pdf
	This report provides guidance on the design, construction, operation and monitoring of permeable reactive barriers (PRBs). It has been prepared for Agency staff assessing third party proposals where a PRB forms part of a remedial strategy, and for problem holders.
USEPA 2000	Subsurface remediation: improving long-term monitoring & remedial systems performance. EPA/542/B-00/002. Office of Solid Waste and Emergency response, Washington D.C.
	http://www.clu-in.org/download/misc/subsurf_proceed.pdf
	This report summarises the presentations and workshops from a conference held in Missouri, 8-11 June 1999. The conference, developed by the Federal Remediation Technologies Roundtable (<u>http://www.frtr.gov/</u>), to address the need to evaluate monitoring and optimising subsurface remedial performance.
USEPA 2005	Roadmap to long-term monitoring optimization. EPA 542-R-05-003. Office of Superfund Remediation and Technology Innovation.
	http://www.clu-in.org/download/char/542-r-05-003.pdf
	This report provides guidance on optimising long-term monitoring programmes associated with groundwater remediation.

Appendix B – Measurement techniques for supporting lines of evidence

This appendix provides an overview of, and partial evidence-base for, the use of supporting lines of evidence from published literature. The cited references can be found in the main References section of this report. Resources given in INFO 4-2 should also be consulted for specific remediation technologies and case studies. This appendix does not represent an output of a comprehensive literature review or provide detailed information on measurement techniques.

B.1 Geochemical indicators

Geochemical indicators form a secondary line of evidence to support natural attenuation by biodegradation. For compounds that are oxidised during biodegradation, such as petroleum hydrocarbons, phenols and PAHs, data on redox potential and electron acceptors (e.g., O₂, NO₃⁻, SO₄²⁻) are informative. For compounds that are reduced, such as tetrachloroethene (PCE), trichloroethene (TCE) and PCBs, data on redox potential and the presence of electron donors (commonly other labile organic compounds than can be oxidised) are informative. In both cases data on breakdown products (metabolites) of the contaminants are important. A decrease in contaminant and/or change in electron acceptor/donor concentrations can be directly correlated to an increase in metabolic by-products (Environment Agency 2000).

The correlation between geochemical parameters and microbial activity can also be used for other biotic systems, for example *in situ* bioremediation or biological PRB (for example Gibert *et al.*, 2007) and abiotic systems, such as the reductive dechlorination of chlorinated hydrocarbons in a PRB (for example Lai *et al.*, 2006) or for redox-controlled immobilisation in soil or groundwater.

B.2 Biodegradation indicators

In addition to establishing the presence of metabolic by-products, biological activity can be measured using respiration rate (Aspraya *et al.*, 2007, Baker *et al.*, 2000, Miller, 1996, Plaza *et al.*, 2005a), although the respiration measured may not relate to degradation of the target contaminants.

An alternative, or additional technique is to look at the number of microbes, by direct count methods or by culturing on specific growth media with or without selective enhancement (plate and most probable number (MPN) counts). Traditionally this has been limited to organisms that are culturable, and when grown on the selected contaminant, can be used to confirm the presence of suitable degraders (see Guerin, 2008 for selective culturing on chlorinated benzenes and Menendez-Vega *et al.*, 2007 for evaluation of *in situ* biostimulation).

Rossello-Mora and Amann, 2001 have estimated that the microbial community in one gramme of soil may contain over one thousand different bacterial species, but less than 1% of these may be culturable. The rapid-growing organisms will be those that are best adapted to the culture conditions and may not necessarily represent the community of

degraders present in the contaminated media (Rappe and Giovannoni, 2003; Gilbride *et al.*, 2006).

Advanced molecular techniques are now available to extract data on the molecular composition from uncultured samples, giving us insight into microbial diversity (Amann *et al.*, 1995; Greene and Voordouw, 2003) and metabolic functionality (Moller *et al.*, 1998; Willson *et al.*, 1999) in the contaminated media. Careful consideration of sampling approach is needed as the planktonic and benthic (biofilm attached to soil particles) samples may show different community structure and function (Ferguson *et al.*, 2007). This is equally important to MNA as it is to engineered PRB.

Malik *et al.* (2008) provides a recent review of molecular techniques currently in use, and a suite of techniques has been used in the UK to support the design of a sequential permeable reactive barrier (Ferguson *et al.*, 2007).

B.3 Remediation process conditions

Operational conditions for process-based technologies are analogous to geochemical and biochemical indicators for MNA, where the relationship between conditions and performance will be established during feasibility (treatability) studies. The advantages of using process conditions as additional lines of evidence are:

- The data are typically already collected to manage the remediation process.
- The data are typically collected at a high density or frequency than samples for laboratory analysis.
- Measurement is typically made using low cost, readily available equipment.
- There is the potential to establish correlation between operating conditions and contaminant reduction during laboratory or pilot treatability studies.

The use of operating conditions is therefore a valid approach to improving spatial or temporal data density providing that correlations can be established and lines of evidence integrated on that basis.

Typical process condition data may include:

- pH (Suthersan, 1997).
- Temperature (Antizar-Ladislao et al., 2006, Stephenson et al., 2006).
- Dissolved oxygen (Suthersan, 1997).
- Injection or extraction rate or mass of reagent (Balcke *et al.*, 2009, Kirtland and Aelion, 2000, USEPA, 1998).
- Soil gas pressure (positive (injection/sparging) or vacuum (extraction)) (Suthersan, 1997).

There is a significant amount of guidance available on remediation processes that includes information on performance monitoring. Some of the references are listed in INFO 4-2, but this is by no means a comprehensive list.

B.4 Bioassays

The primary evidence, contaminant concentration, may lead to a significant underestimate of the toxicity of soil or water contaminated with complex mixtures, such as hydrocarbons (petrol, diesel, coal tar) (Bundy *et al.*, 2005, Plaza *et al.*, 2005b). This is because the contaminant mixture will change in composition, mobility and toxicity with time. Toxicity testing therefore has the advantage over chemical testing because it reveals the generic response to a complex contaminant mixture, that takes into account any toxic metabolites that may not be identified as contaminants of concern. It forms a receptor, rather than contaminant, based approach to risk assessment. The use of toxicity testing therefore holds much promise in verification to help define a remediation end-point based on ecological function.

A case study is presented by Hartnik *et al.*, 2007, where toxicity testing was carried out on separated fractions from creosote-contaminated groundwater. They found that the PAHs, that formed about 85% of the pure creosote, accounted for only 13% of the total toxicity. Other contaminants that contributed to the toxicity, including the methylated benzenes, phenols, N-heterocyclics and alkylated quinolines, may not be identified as risk-drivers in the risk assessment.

A bioassay to assess the generic toxicity of contaminated media will include a variety of tests to assess the response of invertebrates (earthworms), plants (Braud-Grasset *et al.*, 1993) and specific microbes (biosensors) (Hamdi *et al.*, 2007, Salanitro *et al.*, 1997) and may include the response of the indigenous microbial community (Bundy *et al.*, 2005). This is consistent with our current approach to ecological risk assessment (Environment Agency, 2008 a and b). Bioassays are likely to find increasing use for verification of bioremediation approaches and other technologies (and contaminants, for example mixed heavy metals and metalloids) where soil function is an important criterion for the treated material (such as soil amendment or phytoremediation) or where there is a need to demonstrate that indigenous microbial populations are not adversely affected by remediation.

B.5 Geophysical properties

Both surface and downhole geophysical surveying techniques have been widely used in exploration for minerals, oil and groundwater for decades, but have a fairly limited track record in land contamination investigations and remediation performance evaluation. Geophysical surveys are complimentary to traditional sampling methods, and can be used to provide information beyond boreholes, reducing spatial uncertainty (Environment Agency 2002b and c).

Geophysical methods may be used to identify geological and hydrogeological contrasts, such as changes in strata, buried obstructions and depth to water table. For remediation, a range of methods can be usefully applied to identify, for example:

- The presence and degradation of contaminants in a groundwater plume (Atekwana *et al.*, 2004, Naudet *et al.*, 2003, Watson *et al.*, 2005).
- Air saturation in groundwater during *in situ* air sparging (Suthersan, 1997, Tomlinson *et al.*, 2003).
- The long-term operation of a PRB (Kim *et al.*, 2007, Slater and Binley, 2006).
- The efficacy of a geomembrane barrier (for example high density polyethylene (HDPE) barrier).

Geophysical surveys may be best suited to assessing changes in rather than the absolute distribution of contaminants in groundwater as matrix effects (soil/rock media) will not change. Indeed, recently electrical resistivity tomography has been used to support verification of natural attenuation processes, with the proof of concept verified using conservative tracer tracking (Wilkinson *et al.*, 2009).

B.6 Geotechnical properties

Supporting lines of evidence may be established for geotechnical properties that can be controlled during remediation (for example, moisture content during a biopile or turned windrow) or form a specific remediation criterion (for example, the hydraulic conductivity of a containment system (capping layer or slurry wall) or a PRB).

This may involve the use of both field and laboratory measurements. An example of integrated field and laboratory data in common use is the acceptance envelope for compacted clay for a low permeability barrier. The relationship between dry density and moisture content is established for a number of laboratory and field measurements, usually during a pilot trial, and calibrated against laboratory hydraulic conductivity measurements.

B.7 Mineralogy

Mineralogical evidence may be collected during treatability studies or to evaluate the long-term performance of immobilisation (for example soil amendment) and PRB processes. The mineralogical evidence may be used to verify predictions of contaminant mobility (for example, to confirm the formation of pyromorphite when using apatite to stabilise lead in soil (Wright *et al.*, 2005) or to verify the long-term performance of a PRB at a specified milestone following installation (Phillips *et al.*, 2000, Johnson *et al.*, 2008a).

B.8 Tracer tests

Conservative tracers have been widely applied over several decades to measure flow and dispersion in porous and fractured media. The tracers have been selected on the basis that they are not attenuated by physical, chemical or biological processes in the aquifer (i.e. they behave 'conservatively') and that they do not influence the viscosity or density of the groundwater. Common examples of conservative tracers include fluorescein and rhodamine dyes, and bromide and chloride ions. Conservative tracers are becoming commonly used with groundwater remediation projects, for example to verify effective containment or to confirm residence time in a PRB (Bartlett and Morrison, 2009, Johnson *et al.*, 2008b) or air transport pathways during air sparging (Johnson *et al.*, 1997, Suthersan, 1997).

There have been significant developments in the past decade on the use of partitioning and interface tracers, along with conservative tracers, in particular to characterise the NAPL saturation and interface area respectively (Rao *et al.*, 2000).

Partitioning tracers are solutes which partition between the NAPL and water, and the partition coefficients of a number of tracers have been determined in the laboratory. NAPL volume can be estimated from the arrival times of a suite of partitioning and conservative tracers. Interfacial tracers adsorb at the interface between NAPL and

water, and the interfacial area can be estimated from the mass of tracer adsorbed (Setarge *et al.* 1999).

A number of field studies has been reported using interwell methods (Divine *et al.*, 2004, Meinardus *et al.*, 2002, Ramsburg *et al.*, 2005, Simon & Brusseau, 2007, Vane and Yeh, 2002), single well (push-pull) (Davis *et al.*, 2002, Istok *et al.*, 2002) or using a natural partitioning tracer (radon) (Schubert *et al.*, 2007).

B.9 Other changes during biotransformation

A number of techniques have been developed to provide supporting evidence for biotransformation, including:

- Stable isotope fractionation.
- Enantiomeric fractionation.
- Congener distribution.
- Isomer formation.

B.9.1 Stable isotope fractionation

Natural and anthropogenic organic compounds largely consist of carbon atoms with hydrogen, nitrogen, oxygen, sulphur and/or chlorine. Each of these elements have at least two stable isotopes that can be differentiated by mass spectrometry. Isotope fractionation takes place as the activation energies to break chemical bonds differ for light and heavy isotopes, the light isotope bonds being weaker and preferentially cleaved (Meckenstock *et al.*, 2004, Imfeld *et al.*, 2008). For example, the ¹³C-¹²C bond is slightly stronger than the ¹²C-¹²C bond, with the result that bacteria preferentially degrade molecules with the ¹²C-¹²C bonds over those with ¹³C-¹²C bonds. As biodegradation proceeds the remaining un-degraded contaminant becomes increasingly enriched in ¹³C.

Significant changes of stable isotope ratios due to biodegradation have been measured under laboratory and field conditions for chlorinated solvents (Hunkeler *et al.*, 2005, Imfeld *et al.*, 2008, Morrill *et al.*, 2005, Nijenhuis *et al.*, 2007, van Breukelen *et al.*, 2005), BTEX compounds (Fischer *et al.*, 2007, Vieth *et al.*, 2005, Ward *et al.*, 2000), chlorobenzenes (Stelzer *et al.*, 2009), crude oil alkyl-benzenes (Wilkes *et al.*, 2000), naphthalene (Griebler *et al.*, 2004), phenol (Hall *et al.*, 1999), petroleum hydrocarbons (Bolliger *et al.*, 1999, Landmeyer *et al.*, 1996, Pond *et al.*, 2002), fuel ether oxygenates (Kuder *et al.*, 2005, Rosell *et al.*, 2007, McKelvie *et al.*, 2009) and undifferentiated dissolved organic carbon in landfill leachate (van Breukelen *et al.*, 2003). Chemical transformation may cause similar changes, but other attenuation processes (such as dispersion, sorption and volatilisation) have little or no influence on fractionation (Kuder *et al.*, 2005). However, Kopinke *et al.* (2005) showed that sorption onto soil organic matter can lead to fractionation.

Stable isotope fractionation has now been widely used, in conjunction with contaminant and metabolite concentrations and geochemical indicators as a line of evidence to support the existence of biodegradation processes in a contaminated aquifer. This technique may now offer a practical alternative or supplement to microcosm studies for assessing natural attenuation processes and *in* situ bioremediation.

B.9.2 Enantiomeric fractionation

Certain compounds exist as different stereo isomers, known as enantiomers. These enantiomers have the same chemical components, but exists as mirror images of each other, much like your right and left hands. While the chemical components of the enantiomers are identical, the physical and biological properties may differ. Where one enantiomer is more biodegradable that its stereo-isomer biodegradation will be associated with preferential removal of one enantiomer and enrichment of the other in the un-degraded plume. This has been reported for a number of chiral biocides (Lewis *et al.*, 1999, Li *et al.*, 2009), for example the acid herbicide mecoprop (Tett *et al.*, 1994, Environment Agency, 2001).

B.9.3 Congener distribution

During the biodegradation of complex organic mixtures, such as complex PAH or PCB mixtures, the composition of the original mixture changes due to preferential dissolution, volatilisation and biodegradation of labile and light-end compounds in preference to more recalcitrant heavy-fractions (Bamford and Singleton, 2005, Fraser *et al.*, 2008). Over time the undegraded contaminant become enriched in the less degradable and less mobile compounds. Dilution alone would affect all congeners equally, so changes in congener distribution is indicative of biodegradation or other physical process that redistribute mass between phases.

B.9.4 Isomer formation

During the degradation of certain compounds, it is possible to form two or more different isomers, which have the same chemical components but are structurally different. If abiotic processes cause the degradation process the different isomers are typically formed in equal quantities. However if biological processes are responsible there is frequently preferential formation of one isomer.

In the case of the reductive dechlorination of trichlororethene (TCE), for example, abiotic reduction produces equal amounts of cis-1,2-DCE, trans-1,2-DCE and 1,1-DCE. However if biological processes are responsible the dominant degradation pathway is by cis-1,2-DCE. Monitoring for cis-1,2-DCE (relative to the other isomers) can provide evidence of biodegradation.

B.10 Applicability of evidence types to remediation technologies

The types of evidence above have track records, at a commercial or research level, for some but not all of the remediation technologies currently available in the UK. Table B.1 shows the potential use of types of evidence for commercially available remediation technologies in the UK.

Table B.1 Potential types of evidence for remediation technologies.

Remediation Technology	1	2	3	4	5	6	7	8	9
Containment									
Pump and treat									
Monitored natural attenuation									
Ex situ Bioremediation									
In situ Bioremediation									
Phytoremediation/ soil amendment									
<i>In situ</i> chemical remediation									
Soil vapour extraction									
Air sparging									
Soil washing									
In situ flushing									
Stabilisation and solidification									
Thermal desorption									
<i>In situ</i> thermal remediation									
Electrokinetic remediation									

Key:

Supporting evidence	Applicability of evidence
1 Geochemical indicators	Yes, with track record
2 Biodegradation indicators	Possibly, but with limited or
	no track record
3 Remediation process	No, unlikely to be effective or
conditions	relevant
4 Bioassays	
5 Geophysical properties	
6 Geotechnical properties	
7 Mineralogy	
8 Tracer tests	
9 Other changes during	
biotransformation	

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