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TECHNICAL NOTE

Site Selection and Investigations for a Deep Geological Repository: Preliminary Technical Planning in Support of the Stepwise Process

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PROVISONAL or INTERIM status means this Technical Note has been prepared to facilitate Nirex's work programme and does not necessarily reflect the company's final position.

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This Technical Note is part of an ongoing programme of research conducted by Nirex and its contractors. It is a component of the research into options for the long-term management of radioactive waste in the UK.

Nirex want to develop the thinking outlined in this Technical Note through discussions with others. Therefore, this Technical Note should be viewed as 'work in progress' (i.e. interim or provisional status) and Nirex would be grateful for any comments on the ideas put forward. Nirex recognises that the Technical Note only outlines our view and that others may have different views on the issues.

Conditions

Bibliography

A complete bibliography of Nirex publications is available at the Nirex website, www.nirex.co.uk, or from Nirex Corporate Communications at the address below or e-mail: info@nirex.co.uk.

Feedback

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PREFACE

Nirex produces a number of Technical Notes, on a variety of subjects, to inform the debate on what the UK should do with its radioactive waste. These are often accurate at a particular point in time and will change as a result of further thinking, comments from other interested parties and the results of further research. They are thus regarded as ‘work in progress’, but we feel that given the nature of the debate that it is beneficial to release them at this stage. It must be recognised that they may be updated and amended over time.

This Technical Note reports on one of a number of pieces of work that are being carried out as part of a review of the requirements for a site characterisation programme. The results and conclusions contained in this piece of work do not in themselves represent Nirex’s final position on this topic. However, they will be used to inform the development of an overall strategy for site characterisation.

The programme and cost for site characterisation given in this report can be taken as an upper bound estimate. Nirex recognises that there could be significant benefits in terms of minimising environmental impact, cost and duration of site characterisation if a different approach, which could for example utilise mobile, small diameter drilling rigs, were to be adopted. Consequently a study is underway to establish the feasibility of this and will be reported later this year.

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SITE SELECTION AND INVESTIGATIONS FOR A DEEP GEOLOGICAL REPOSITORY: PRELIMINARY TECHNICAL PLANNING IN SUPPORT OF THE STEPWISE PROCESS

1 INTRODUCTION

This note outlines the technical aspects of a potential site investigation programme in support of the stepwise process for developing a solution for long-term radioactive waste management. There are two drivers for considering site investigations at this very early stage in the development of radioactive waste management policy. These are:

- the continuing need to provide advice on resource planning to producers and managers of radioactive waste, based on an up to date view of the costs of implementing phased deep disposal
- the importance of demonstrating coherent and well developed ideas about integrating technical work, societal issues and consultation at all stages in the stepwise process.

This Technical Note reports on one of a number of pieces of work that are being carried out as part of a review of the requirements for a site characterisation programme. The results and conclusions contained in this piece of work do not in themselves represent Nirex's final position on this topic. However, they will be used to inform the development of an overall strategy for site characterisation.

Ongoing packaging standards, specifications and advice are based on the current Nirex concept of phased deep disposal. Therefore, this note describes a site investigation methodology for a deep geological repository for the wastes currently within the Nirex remit (i.e. 263000 m^3 of solid ILW and some LLW). This disposal concept requires that the geological characteristics at a potential repository site be adequately investigated to provide a description of the geosphere that is suitable for assessments of radionuclide migration and retardation. A knowledge of the evolution of the geosphere, over time scales of relevance to safety assessments – typically up to one million years, also provides a basis for demonstrating the stability of the engineered barriers in the disposal concept. Alternative site investigation methodologies may be required for alternative concepts or for different assumptions about the nature of the wastes for disposal.

Given the importance of supporting a stepwise approach to developing a strategy for radioactive waste management, the proposed methodology outlined in this note is also staged, and progresses from general considerations to detailed site characterisation in a number of steps. A staged approach to the implementation of siting investigations is a sensible use of limited resources because it starts with the generation of a broad understanding from regional studies and continues with the acquisition of progressively more detailed knowledge about geological conditions in smaller areas as the investigations focus-in on particular locations for a potential repository and specific aspects of the repository environment.

The note is structured to present some basic terminology and the broad principles concerning the 'process' involved in a site investigation programme in Section 2. This is followed in Section 3 by a discussion of the stages of a possible site investigation programme, how they relate to the various phases of the stepwise process and how they might be integrated with the main steps of consultative participation outlined by Barker and

Hunt[1]. Section 4 sets out the main factors (assumptions) that could modify the cost basis for the technical programme outlined in this report. The assumptions adopted in developing ideas about a future site investigation programme and Section 5 provides the main bulk of the note and discusses for each stage, the aims, relevant site investigation techniques, their interdependencies and their end use, programme and resource implications.

2 TERMINOLOGY AND PRINCIPLES

Throughout this note 'site selection' refers to the process whereby information is gathered, options are considered and decisions are made on alternative areas that might be suitable for hosting a deep repository.

The term 'site investigation' is a broad term used widely in civil engineering and environmental studies that covers those activities that provide information concerning a particular site. As such it can include desk studies and the compilation and interpretation of existing data. Site characterisation, however, is a more specific term used in radioactive waste management for detailed surface and sub-surface geoscientific investigations that are intended to provide new knowledge concerning site conditions and the physical processes that are important for a thorough understanding of the local system. Site characterisation generally includes data acquisition activities and interpretation of the resulting information.

The site selection and characterisation methodology described in this note has been developed to respond to the following principles:

Consistency with the stepwise process, in which is embedded the concept of integrated technical work, societal research and consultation.

Application of best practice within the range of site investigations and characterisation, recognising that different industries (e.g. civil engineering and environmental) place different requirements on site investigation programmes.

Equivalence with other radioactive waste management programmes internationally, paying particular attention to the site investigation programmes currently being implemented by POSIVA (Finland), SKB (Sweden) and ANDRA (France), but also recognising the influence of national culture and legislation.

Critical evaluation of the Dounreay and Sellafield site investigations performed by Nirex during the late 1980's and 1990's.

Awareness of potential legislative requirements, in particular those stemming from Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA) directives, UK planning legislation and regulatory regimes.

Consistency with considerations of societal research and consultation during site investigations[1]

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[1] F. Barker and J. Hunt, *Consultation/Participation During Site Investigation and Selection*. A contractor approved Technical Note to Nirex, 2003.

3 INVESTIGATIONS, IN RELATION TO THE STEPWISE PROCESS

Nirex has proposed a stepwise approach to radioactive waste management[2]. This approach is generic and does not focus on a single disposal option. However, a possible solution for long-term radioactive waste management, and the option that Nirex has a great deal of experience in researching, is deep geological disposal. This note considers the technical factors that need to be considered as part of a preliminary site selection and investigation programme specifically for the deep disposal option.

Barker and Hunt provide proposals on the main steps that should be included in a consultative site selection programme. Following policy formulation, institutional resourcing and consultation about site selection criteria, they identify the need to:

- Identify potentially suitable areas
- Identify a "long-list" of potential sites
- Identify short-listing criteria
- Identify a short-list of potential sites
- Identify further short-listing criteria
- Identify sites for detailed investigations.

Essentially, the proposals by Barker and Hunt advocate a screening process within which the above steps could be used to form a convenient framework against which to establish a technically driven site investigation programme. Such a programme would necessarily be carried out in an environment where stakeholder participation and consensus is provided at key stages in the process.

Site selection needs to take account of international best practice in site investigations [3,4]. Such work sets a technical precedent that site investigations should commence at large regional scales, with successively more detailed investigations being undertaken at smaller scales, until one or more specific sites are recommended for detailed site characterisation. Technically, different stages of a site investigation programme are distinguished by: the scale of the area(s) being investigated; and the level of detail applied to that investigation[5].

Figure 1 illustrates this concept of decreasing scale as a site investigation programme proceeds.

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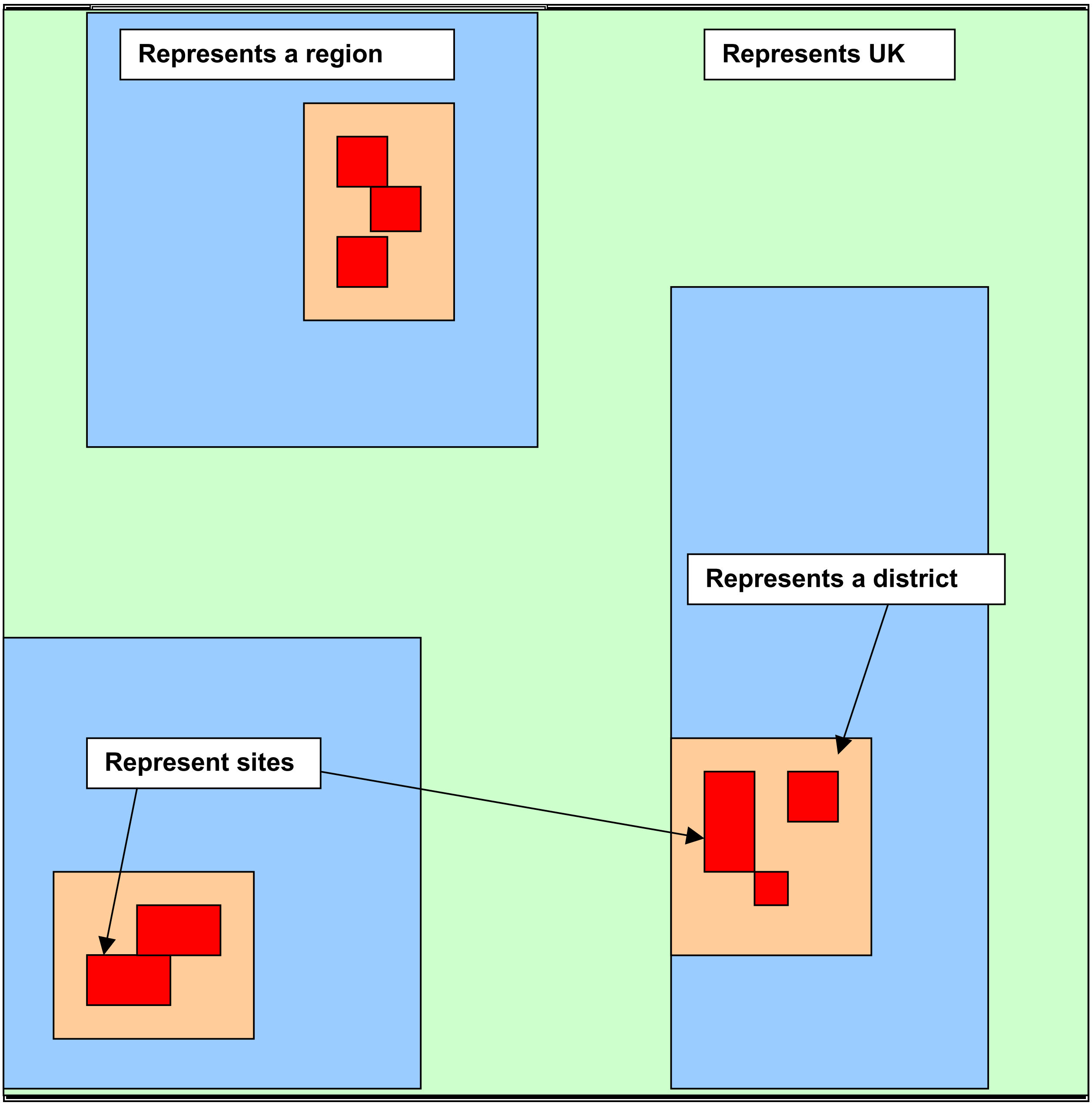
[2] E Atherton, *A Stepwise Process For The Implementation Of A Long-term Solution For Long-lived Radioactive Waste In The UK: "The Nirex Stepwise Process"*, A Nirex Technical Note, 2003.

[3] T. McEwen and T. Aikas, *The Site Selection Process for a Spent Fuel Repository in Finland – Summary Report*., POSIVA Report 2000-15, 2000.

[4] SKB, *Site Investigations: Investigation Methods and General Execution Programme*, Report TR-01-29, 2001.

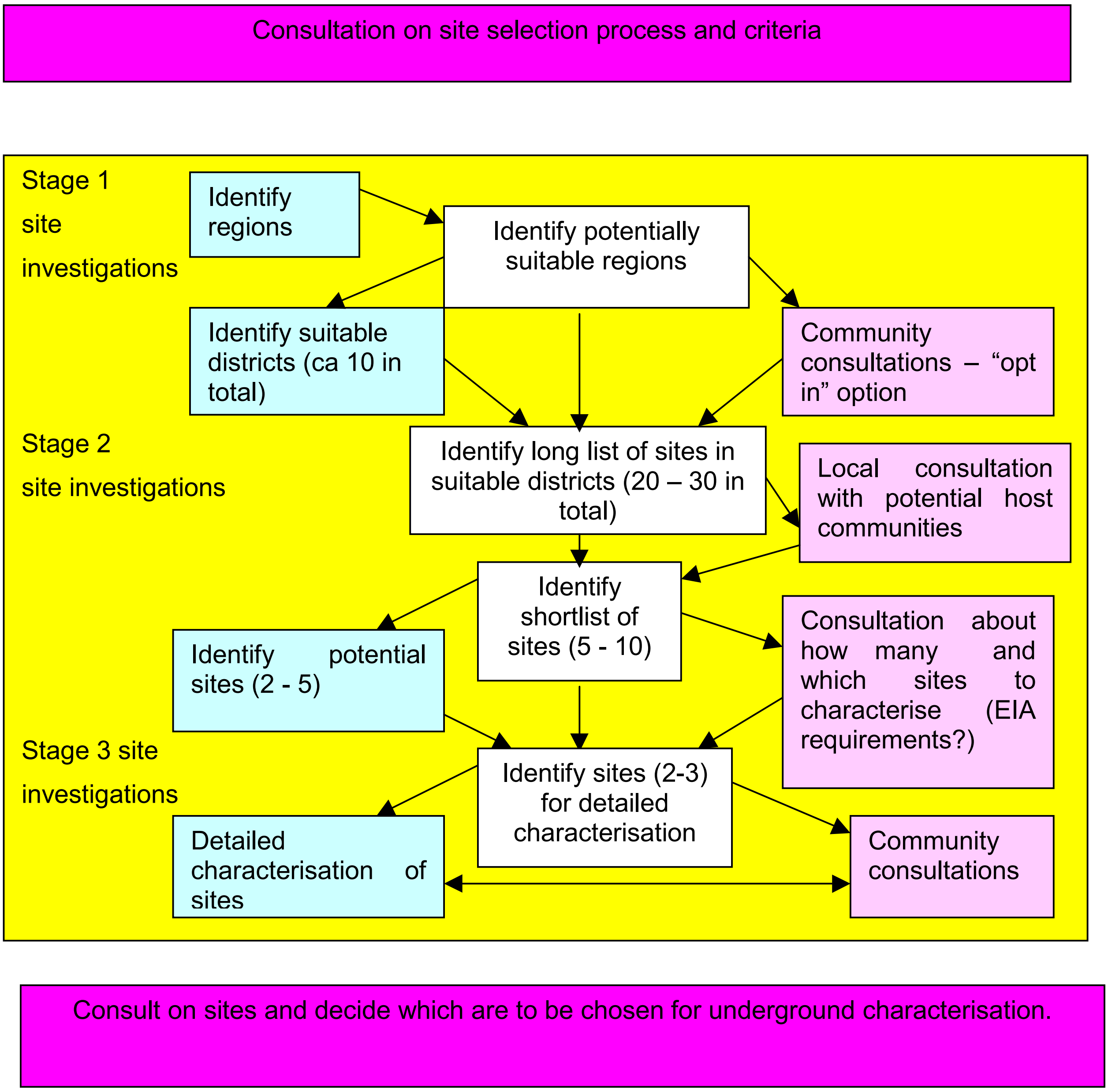
[5] IAEA, *Site Investigations for Repositories for Solid Radioactive Wastes in Deep Continental Geological Formations*, IAEA Technical Report Number 215, 1982.

Figure 1: A schematic of the different scales of investigation



Based on Figure 1, we propose three stages to a site selection and investigation programme. The stages proposed could be integrated into the screening process identified by Barker and Hunt. The three proposed stages are shown in Figure 2. In this note, we have considered surface based investigations only. We have not considered a final stage in a site characterisation process that might include the need for an underground laboratory. At each stage in the process, decisions will have to be taken to determine whether the next phase can commence. As discussed by Barker and Hunt, such decisions are likely to be taken on the basis of both technical evaluation and broader stakeholder agreement. Consultation will therefore be a continuous and integral part of the site investigation programme.

Figure 2: Integration of site investigations and consultation Stages in a site investigation programme Detailed steps identified by Barker and Hunt (2003)



Three questions will determine the scope (extent, aims and objectives) of site investigations for each stage.

- what is being investigated at each of these stages?
- what methods should be used?
- to what end?

The consultative site selection process described by Barker and Hunt, in particular the site evaluation criteria identified within that process will be very influential in answering the above questions and in determining the scope of the investigations at each stage. The idea is that consultation and consensus (as far as is practical) will be at the heart of identifying site selection and evaluation criteria, in particular that a given, staged process is acceptable. For the purpose of this paper, assumptions about the technical criteria that will be adopted have been made. These assumptions have been based on the site characteristics required to make the phased disposal concept work. A broad description of what is anticipated at each of the three stages is given below:

STAGE 1 Identify suitable regions and districts: Initial work would involve desk based studies to distinguish large scale regions (>100 X 100 km) of mainland Britain[6] that might be suitable for more detailed investigation. This would be achieved by identifying and excluding regions of the country that are clearly unsuitable for siting purposes.

Nested within the regions that contain potentially suitable environments for disposal, the Stage 1 study would continue in order to identify smaller scale districts ($400km^2$ to $2500 km^2$, i.e. 20 x 20km to 50 x 50km) that could be potentially viable locations for hosting a repository. The focus for this stage of the work would be to identify areas providing relatively consistent geology and environmental conditions likely to be amenable to investigation. These districts will generally be on a scale equivalent to administrative areas governed by district or borough councils. The work would be desk based, but may extend to visiting local information sources. Non-intrusive techniques could be considered at this stage (such as airborne geophysics or satellite imagery) in order to ensure that the various districts are considered in an appropriate level of detail (and to avoid any bias in decision making on the basis simply of what we already know). But the implications for this type of activity on local perception will need to be carefully considered.

The Stage 1 investigation activities are likely to focus on districts in which the communities have indicated an interest to opt in (if that approach is taken). In this case, it may be easier to consider the use of some non-intrusive investigations, but the primary aim would be to evaluate whether there are technical reasons to rule out the borough from further consideration. Of the order of 10 districts could be reasonably considered to remain from the Stage 1 evaluation, from a cost and logistical (time) standpoint. The 10 or so districts would each provide some promise that a volume of rock mass exists locally that would provide the stability necessary to construct a repository and protect the engineered barriers from environmental change in the near surface. Additionally, preliminary prognosis of the geosphere system would indicate that radionuclide travel times may be acceptably low and dispersion sufficient to ensure a robust geosphere barrier function. Several different types of geological environment and setting are likely to provide such preliminary promise.

[6] It is assumed that offshore islands and Northern Ireland would be excluded from consideration because of transport (cost) or legal reasons. However, this assumption should be thoroughly re-evaluated at a later date.

STAGE 2 Identification and evaluation of potentially suitable sites: Within the districts identified for inclusion in the stage 2 study, work would commence to identify one or more districts that could contain sites that would be considered for further, more detailed, investigation (probably up to a maximum of four sites in each district). The long-list of localities for investigation in Stage 2 is therefore likely to represent between 20 to 30 sites. The focus of this stage of the investigations would be to develop outline conceptual models and compile more detailed data on the geological, hydrogeological and surface environment at the sites, sufficient to enable some form of comparison. Such investigations would probably include limited use of a more comprehensive suite of non-intrusive techniques to establish a broad understanding for the surface environment, the deep geological structure and the groundwater system at the sites. Hence a suite of geophysical measurements, and perhaps a limited number of shallow and deep boreholes could be considered, including renovation of pre-existing boreholes. Key technical criteria will be indications of low groundwater flow rates, geological stability, lack of economic resource potential and constructability. The work will need to be sufficiently extensive, and carried out at a sufficient number of alternative sites to meet the option evaluation requirements of an EIA. In this respect, a consideration of environmental impacts likely to result from Stage 3 investigations and repository construction will need to be assessed for each site.

STAGE 3 Detailed site characterisation: The precise number of sites identified for detailed evaluation should be defined nearer the time, based on acceptable disposal system considerations and continuing consensus. By this point, the local communities should have been fully involved in discussion and consultation with Nirex or a successor waste management organisation, in particular as part of the evaluation of potentially suitable sites identified above. The focus of detailed site characterisation would be to determine the suitability of a particular site(s) for locating a facility. Suitability can be assessed in many ways and, in the future, suitability will probably be defined more broadly than has previously been the case. This is in line with the current Nirex mission and values and other legislative developments such as the EIA and SEA directives and the Aarhus Convention. Consequently, the definition of suitability will likely be assessed in relation to the degree of public acceptance of the proposals, as well as to the level of regulatory compliance indicated by a site specific performance assessment. Site investigation and characterisation will have a key role in informing consultation and decisions about suitability at each step in the development process.

The objectives of the site characterisation programme therefore need to be:

- Developing a good understanding of the geological and environmental features and processes of the site, today and in the past, and synthesising these into an understanding of the complete system relevant to radioactive waste disposal.
- Producing a comprehensive database of the site parameters, including data required to establish baseline conditions.
- Responding to technical concerns on site issues, as expressed by key stakeholders such as regulators, the wider scientific community and local liaison groups.
- Providing information, that is transparently and readily available to all stakeholders, to support performance assessment and developing a wider safety case.

These investigations will also cover all the civil engineering and environmental issues typically expected from an investigation for a major development project

4 SITE INVESTIGATION STRATEGY – UNDERLYING ASSUMPTIONS

The surface based investigations of the Sellafield area were never completed by Nirex. At the time of the Secretary of State's decision in March 1997, a major 3D seismic survey to resolve the detailed structure of the repository volume was still outstanding, as was the drilling of several new deep boreholes to better investigate the geology and groundwater features of the sandstone sequence overlying the host rock. Therefore, the Sellafield costs up to 1997 are not representative of the full costs of a surface based investigation at that site.

In Section 5, techniques, methods and costings for the stages of a site investigation strategy are proposed as a preliminary basis for further more detailed studies. In this section a range of considerations and assumptions affecting those proposals are identified.

4.1 The nature of the site investigation process

The objectives of a site investigation are very rarely met by the acquisition of data alone. There needs to be subsequent steps of:

- data processing - to transform measurement data of site parameters into information that is meaningful in terms of the properties of the site;
- interpretation - to understand the significance of that information in terms of the individual aspects of the site (e.g. groundwater flow, rock mechanics, environmental processes etc.); and
- integration - to develop a self consistent understanding of the site as a whole and that includes all the individual aspects.

Modelling may be used at any of these subsequent steps, as appropriate. Additionally, there needs to be concurrent data management of results (both raw, processed and interpreted). This data management can become very complex as site investigations progress.

All these steps have been taken into consideration in the proposals presented in Chapter 5. Although the cost of data acquisition is a significant component of the overall costs, it is of little value without an efficient means of capturing and sensibly applying the data.

Acquisition, processing, interpretation and integration are generally undertaken in an iterative manner, which leads to the idea of investigation cycles (Figure 3). If results from these studies are used in the assessment of long-term performance as a measure of site suitability, then the cycle becomes an assessment cycle. It is assumed that each of stages 1,2 and 3 constitute an assessment cycle in their own right. However, during Stage 3, a number of investigation cycles should be undertaken. The number of cycles will be determined on the basis of the level of scientific understanding of the site. However, it will be necessary to determine in advance the criteria that will be used to assess when that understanding is sufficient.

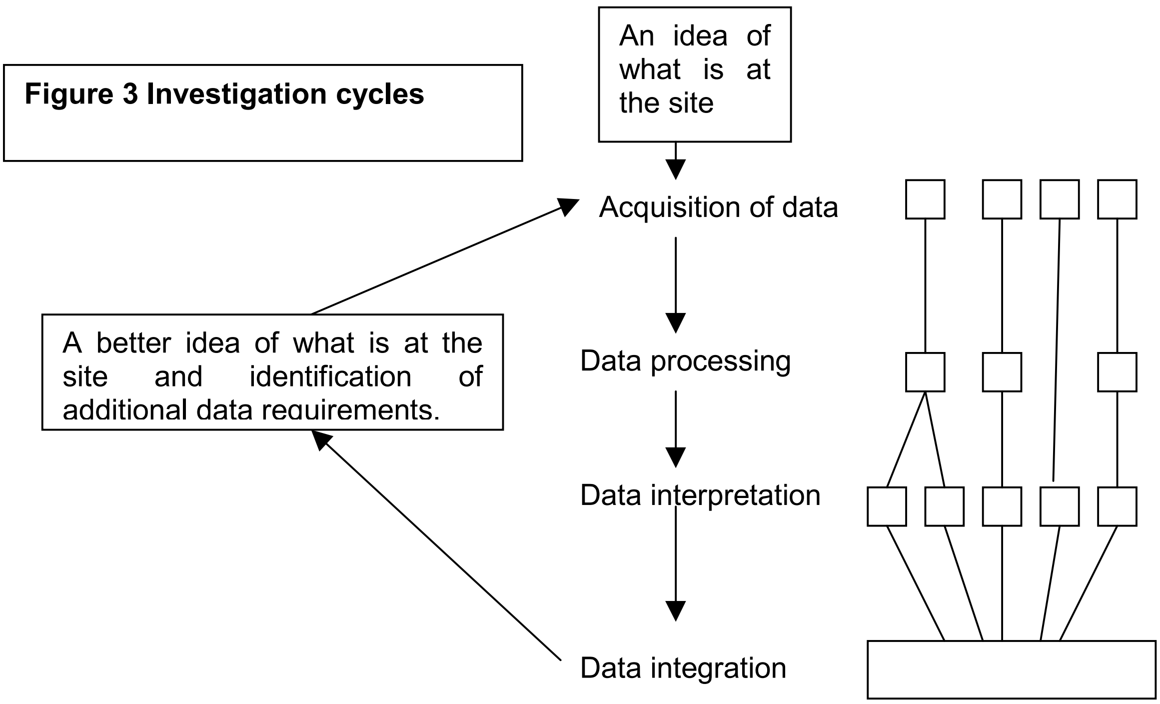


Figure 3 Investigation cycles

4.2 The nature of a Waste Management Organisation in managing a site investigation programme

It is assumed that Nirex or a successor will continue as a proactive non-profit making management organisation with sufficient internal resources that allow it to commission work in an educated manner. Thus, the majority of the investigation work 'on the ground' will be carried out by external contractors, but Nirex or its successor will plan, specify, check, synthesise and apply the results of such work. On the basis of the technical results being collected, it is envisaged that Nirex will put forward regular reports and recommendations to an overseeing body that has direct input into the programme and has a role in decision-making about when sufficient understanding of a site has been acquired. The information, both raw and processed, would also be made widely available to interested stakeholders in a timely manner.

4.3 The nature of the wastes

The assumption made in developing this site investigation methodology is a waste inventory of 263,000 m^3 for solid ILW and certain LLW. Additional volumes of these types of waste would not necessarily place significant additional caveats on the programme outlined here. It is unlikely that there will be a significant increase in costs associated with characterising a site for high level wastes alone, but a co-disposal option for both intermediate and high level wastes would probably entail a significantly larger repository footprint[7] and the need for more detailed investigations of particular or additional aspects

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[7] S King and M Poole, *Issues Associated with the Co-disposal of ILW/LLW and HLW/SF in the United Kingdom,* Waste Management 2002 Conference, Tucson, Arizona, 24-28 Feb 2002.

of the rock mass (e.g. thermal properties) and therefore there would probably be an additional cost element. These additional costs have not been evaluated.

4.4 The nature of the site(s) being investigated

The costs provided in Section 5 are for deep geological disposal in a Sellafield-like type of rock environment. Investigations in different rock environments or for other options are likely to result in different costs.

It should be recognised that some sites may require less investigation than was carried out at Sellafield (because of a more predictable sub-surface environment), whilst other locations may require more expenditure (because of greater complexity). It will not necessarily be possible to anticipate with accuracy the degree of sub-surface uniformity (that should result in greater predictability) at the outset. In fact it is often the case that during an investigation, the confidence one has in the nature of the sub-surface environment goes through cycles of increasing then decreasing confidence. A key point in this regard is the development of a defensible strategy to deal with parameter and conceptual uncertainty.

Investigations are presumed to be limited to sites on mainland Britain only, although the options for considering off-shore islands should be fully debated in any future work.

There will be a cost involved in transporting equipment and personnel to the investigation sites. Naturally, such costs will increase with distance from the main conurbations or sites where equipment is held. This note does not breakout explicitly the costs that might be associated with remote sites. They are based on an expectation for investigations in ‘reasonably accessible’ locales.

In Section 5, we have provided estimates for the number of Districts/Sites potentially to be investigated during stages 2 and 3. These numbers are based on our estimates about the likely number of areas that would be (a) broadly required by stakeholders to allow for comparisons between an adequate number of alternative areas and (b) feasible within realistic cost and logistical constraints. The latter mainly relates to the availability of sufficient expertise and equipment over reasonable time scales.

4.5 The relationship between site investigations and underground research

The objectives, methods and costs outlined below are for surface based investigations only, i.e. they do not include the costs or aims for an underground laboratory. An underground laboratory should be considered essential in order to derive detailed site specific information on the true spatial relationships between some of the essential parameters. Nevertheless, there is some debate over whether the decision to investigate underground should be taken as part of the overall site selection and investigation programme, or as a first stage in a repository development programme. Therefore, it has not been considered here, but this issue should be addressed (resolved) during the policy review process.

4.6 Factors *not* taken into account (costing caveats)

The costs provided in Section 5 are external contracting costs for technical work only. They do not include an estimate of costs associated with consultation (see Barker & Hunt Technical Note). The costs associated with the employment of Nirex staff to work on the technical programme have not been factored in, however, an outline cost estimate based on the requirements for a Nirex site characterisation team could be readily made.

The investigation costs are based on an in-house assessments of current prices for geoscience services. No external organisations have been approached to verify these estimates. Until such verification is made, the costs contained in this note should be considered as provisional estimates and should be treated cautiously.

It is assumed that ownership of land and mineral rights will not act as constraints on the siting/routing of investigation work and any additional costs that might arise in relation to such issues have not been factored into the cost estimates.

There are likely to be costs associated with progressing planning and other permissions for boreholes and other surface based activities. It is also recognised that current legal advice suggests that an Environmental Impact Assessment will be required in support of each application for the development of a borehole. These ancillary costs have not been included in the estimates provided.

It is not clear what role regulatory bodies might have in any future investigation programme, although Nirex strongly advocates their early involvement. Based on the Sellafield experience, and possible future developments, it may be necessary for the waste management organisation to cover costs associated with regulatory reviews and audits, and possibly for the involvement of the regulators in public consultation exercises. Furthermore, there may be a requirement for the waste management organisation to commission and fund additional investigation activities or extensions to planned technical activities that the regulators (or other bodies) may deem necessary. No allowance has been made in the cost estimates provided in Section 5 to take account of any influence the regulators might have on technical content, over and above that judged necessary by Nirex.

The site specific work undertaken by Nirex would be augmented by scientific studies that have generic applicability and are carried out elsewhere (e.g. natural analogues, experiments in overseas underground laboratories). The costs for this type of work are not included here.

Advances in scientific understanding and the sensitivity (resolution) of investigation techniques over the past decade now mean that more precise (and accurate) information can be collected. For example, processing of seismic reflection data is now routinely carried out at higher resolution spatial scales than was the case a decade ago. This factor will improve confidence in radiological safety assessments, but may mean increased costs in comparison to previous simpler, less rigorous investigation programmes.

The costs are to be incurred at an unspecified time in the future and will likely run over several years (possibly up to or beyond 16 years). No discounting values have been applied to the cost estimates in this note.

The costs do not include any additional components related to contingencies or risk factoring.

In the same way that technological advances since Sellafield have been built into this cost evaluation, future advances prior to an active investigation programme might similarly become significant. They may affect labour and equipment costs. The costs in this note should therefore (a) be verified by reference to external service providers and (b) should be periodically updated.

A key factor affecting planning is that the site investigation programme must not only be linked to the requirements of the repository design and engineering programme, but also to the performance assessment programme (including the needs of wider safety assessment). There will need to be, therefore, a great deal of interaction and synergy between the 'three teams' from characterisation, engineering and assessments. Any additional costs involved in this fundamentally important aspect of any future investigations are not explicitly included in detail at this stage as ideally they should largely be under the immediate control of Nirex and therefore included as part of the operational costs of Nirex. However, it will be essential to properly programme-in such interactions at an early stage of any investigation process and to properly evaluate any additional expenses that might be incurred by external contractors. As guidance, the summary figure at the back of this technical note provides an illustrative assessment of the costs that might be incurred for supporting technical evaluations of continued district or site suitability and performance assessments. The issue of site investigation and performance assessment interaction is considered further below since it has a fundamental impact on the timing of a site investigation programme.

4.7 The relationship between site investigations and performance assessment

In the past, the key driver for Nirex's site investigations were seen to be:

- The provision of information necessary for the design and construction of a radioactive waste disposal facility
- the provision of input data for assessment work calculating the long-term safety performance of a facility located at that site.

Despite a potentially broader role for site investigations in informing consultation and decision making, the need to provide inputs to performance assessment and design will remain key drivers for the site investigation process. This requirement will place constraints on the investigation process. Our assumption is that a technical evaluation to assess continuing site suitability or a series of performance assessments will be undertaken to support each key decision point (leading to a move from Stages 1, to 2 to 3) in the Nirex stepwise process. The nature of these assessments has been discussed in more detail elsewhere[8]. Past experience suggests that a time period of 18 months to two years is required for the production of each assessment. A future site investigation programme will need to address the question of whether site investigations and characterisation continue during the production of an assessment, or whether investigations are suspended. The answer to this question may lie in the way in which performance assessment is seen to contribute to consultation and decision making as part of the stepwise process. Our assumption is that in the early phases of the investigation programme, the investigations contribute much more to the overall site selection process than solely via a related performance assessment. In these early stages, there will not be sufficient site specific information to contribute all the input parameters required by a full performance assessment. It is during stage 3 that the issue becomes critical and the relationship between site investigations and performance assessments needs to be addressed. We have therefore assumed that site characterisation will continue during the production of one or more performance assessments and that a 'data freeze' will support the production of the performance assessments. However, it will need to be made clear how ongoing investigation results (which might post-date the then current performance assessment) can contribute as part of the consultation identified between each investigation cycle. It is recognised that this is

[8] L. Bailey, *Performance Assessment in Context*, A Nirex Report, Work in Progress.

a sensitive issue and that decisions might be made to completely halt active field investigations whilst consultation is underway. However, it is argued that this would be an inefficient use of limited resources and the benefits of allowing some continuity in surface based investigations during Stage 3 should be discussed.

4.8 Where things have changed since Sellafield

There are a number of assumptions we have made based on the lessons learned during the Sellafield investigations. Whilst these assumptions relate primarily to the detailed characterisation stage, it is worth identifying them here since they will tend to dominate the overall costings. Key differences in the approach that might be followed in the future relate to the following issues:

- It is to be anticipated that the commercial terms offered to external suppliers would be rigorously negotiated to achieve best value for money. Agreements with suppliers would include contract costs to cover the provision of management services and purchases on behalf of Nirex. During the Sellafield investigations, a cost-plus model was usually used by contractors for billing Nirex. In the future it would be sensible to consider using Nirex in-house purchasing and finance resources to a greater degree, to allow much of the administration and ancillary management to be carried out without additional expense. Consequently, in this note no allowance has been made for any additional costs arising from e.g. a mark-up on goods and services or as management fees.
- It is recommended that intermediary agents should not be used (e.g. as CEGB and BNFL were used in the shallow site investigations and the early Sellafield stages) due to increased management costs, little control by the waste management organisation and communication inefficiencies. However, it may be advantageous to use the services of a preferred consortium of contractors for much of the ‘routine’ investigation work, with the proviso that this arrangement is reflected in reduced rates overall. Tight management control will be required to ensure that one consortium or company does not dominate the investigations in such a way as to reduce the potential for competition or stifle scientific objectivity.
- A commercial distinction between contracts for the acquisition of data and contracts for its interpretation may not be helpful in developing a well managed and integrated programme. For the Nirex investigations in the Sellafield area a decision was made to separate out the acquisition activities from interpretations. For the future, there may well be significant economies if some contracts are let to a company (or consortium) for both acquisition and interpretation. Providing sufficient peer review of methods and results is made, there should not be a conflict. In some cases, ease of communication between acquisition and interpretation groups within the same organisation (e.g. work could be carried out by the same people) would provide iterative cross checks on the on-going acquisition/interpretation and therefore should result in enhanced technical value. Each case will have to be viewed on its own merits as it may be judged appropriate to divorce acquisition from interpretation in certain cases. This does not necessarily impose extra costs since it is mainly a matter for the Nirex team to balance benefits and disbenefits, but it needs to be considered in setting up contracts for site investigations.
- It should not be necessary to fully core all the deep boreholes that are drilled at a site. It will be justified to plan and drill boreholes for narrowly defined objectives (e.g. core, hydrochemistry, geotechnics etc.) and in this respect much more cost effective drilling methods could be applied in the future. Drilling methods have also advanced in recent

years and techniques such as air flush circulation and directional/horizontal drilling (to better characterise near vertical structures) are much more commonly applied.

- In recent years there have been significant advances in (a) non-intrusive geophysical investigation techniques, (b) interpretation techniques, including those that generate statistically valid stochastic realisations of the data and (c) the use of ‘soft’ data and Bayesian updating to further improve data interpretations. These advances would be fully utilised in a future investigation programme in order to better describe the spatial variability in key parameters.
- In line with requirements for Environmental Impact Assessments and to better understand the effects of near-surface perturbations on groundwaters at depth, more effort will need to be made to characterise the near-surface flow regime and present day surface environmental conditions at sites chosen for detailed investigations.
- At Sellafield, a large amount of effort was put into characterising the present day groundwater flow field at depth. This would also be the case in the future, but, taking into account our appraisal of trends in performance assessment, which are dealing more creatively with “soft” data and time dependence, it is suggested that greater effort will be put into characterising (i) the spatial variability of properties important for radionuclide transport and (ii) the nature of time variant changes in the flow and transport conditions. A major consideration in this regard will be the need to characterise the uncertainty in the spatial and time varying groundwater flow field and transport properties (as well as deriving ‘representative’ single values based on present day conditions).
- The significance of the effects of the length or volume of the scale of measurement on several parameters was not fully accounted for in the Sellafield investigations, especially with respect to groundwater flow and transport (e.g. permeability). An objective of a future site investigation programme will be to understand the way that the properties of interest vary over various measurement scales over the volume of interest. Therefore, investigation methods that provide multiple measurements at various scales over the volume, rather than an individual measurement at the scale at a point, are of more benefit and a wider spread of hydraulic testing at different measurement scales will be required to enable a more thorough consideration of scaling issues.
- With a more consultative approach to site investigations, and a better relationship with the local community, we assume that a future site investigation programme will not “drip feed” plans for boreholes and major acquisition activities into the planning process. Rather, we would envisage scoping out proposals for a full programme of data acquisition, encompassing many complementary techniques. These proposals could be subject to deliberation and consultation during the permitting process. Having said that, it is recognised that during any site investigation programme the characterisation priorities and research objectives might change, to varying degrees, in response to the identification of new, potentially important uncertainties. There will therefore be a strong onus on the waste management organisation to effectively communicate and, where necessary negotiate, with local stakeholders on what might be considered ‘day to day’ issues and changes in work activities.

The consultative approach that is proposed means that the overall time required to undertake the investigations will not necessarily be less than was the case for Sellafield. It is likely to be greater. However, within that time period, we envisage a more efficient use of time and resources on site investigations, and greater confidence in the justification for the work undertaken at any stage.

4.9 General considerations for a future programme

- Site investigations need a co-ordinated and multi-disciplinary approach.
- Non-invasive methods should be used as much as possible, in order to maintain the integrity of the geosphere barrier.
- A key factor in the Inspector's report on the Sellafield Public Inquiry[9], concerned the establishment of baseline conditions. It will be necessary to initiate and maintain long term observations of key parameters in order to ensure that the baseline dataset is established (against which future impacts can be evaluated). Instrumentation to allow long term monitoring should be installed sequentially during stage 3 investigations as boreholes are drilled and the surface-based environmental research programmes gets underway.
- At the detailed planning stage, it will be necessary to engage the best scientific advice possible, both in order to ensure that plans are thorough and scientifically defensible and also to ensure that there is involvement by peer groups not involved in day to day decision making. A high-level expert review group should be used by the waste management organisation to review preliminary plans and to improve on them if required. This is likely to incur expense at an early stage in the programme, but precise costs will depend on the composition and when such a group is formed and what its precise terms of reference will be. It is suggested that a small technical expert panel be convened with up to half a dozen named individuals from outside organisations (e.g. academic scientists and international experts not already co-opted onto a Radioactive Waste Policy review body or other oversight commission). It would be sensible to consider combining this technical expert group with a panel of experts chosen for their expertise in the social sciences or as representatives for wider society.

5 SITE INVESTIGATIONS – TECHNIQUES, METHODS AND COSTINGS

In this section, a detailed discussion on the nature of a site investigation programme for each of the three identified stages is presented, based on the assumptions outlined above.

5.1 Stage 1: Identification of Regions and Districts

This stage is likely to involve generalised investigations at a large scale (>100x100km), identifying whole regions that satisfy broad requirements followed by more detailed investigations to identify Districts of size 400km^2 to 2500 km^2 (e.g. 20x20 km to 50x50 km). It is likely to be an almost exclusively desk-based study, utilising existing information. Stage 1 can be considered in two parts conceptually, but for financial economies and manpower efficiency the two parts would be seamless.

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[9] Report by C.S. MacDonald, *Inspector to the RCF Planning Inquiry*, to John Gummer MP, 21 November 1996.

Assuming that deep geological disposal is the preferred option, early in the siting process (preferably pre-Stage 1) it will be necessary to agree on the types of geological environment that can be considered to be most suitable for hosting a repository or making up the overlying geosphere. The body (e.g. a Radioactive Waste Policy Board) charged with responsibility for overseeing the activities of Nirex or its successor waste management organisation would probably want to stipulate this, but Nirex and its expert panel should be proactive and make recommendations as to the criteria against which regional evaluations should be judged. It is to be emphasised that it is the total environment, not a particular rock-type, that will allow a safety case to be made. Having said this, preliminary studies presented in “Evaluating Performance” (Nirex Report N/011) have informed us about the general environments that are likely to be promising for detailed studies.

Crystalline rock does have intrinsic properties that make it an excellent host rock for a repository. These properties relate to the low ingress of groundwater into the repository and well defined geotechnical characteristics that would facilitate repository construction. Massive limestones or indurated clay rocks also possess the characteristics of very low matrix permeability and geotechnical strength and could also be considered as a host rock environment. Salt strata (e.g. halite) could be an excellent host rock, due to its extremely limited groundwater flow and its propensity to deform plastically (i.e. self-sealing), but in the UK it is not clear that there are sufficient thicknesses present. The salt would have to be ‘massive’, i.e. homogenous, without inter-layers of sandstone and siltstone that might act as fast pathways for fluids, and any halite strata would have to be up to 30-50m thick at least.

Because the UK safety assessments for intermediate level waste do not presuppose 100% containment for an extended period of time (unlike high level waste concepts in e.g. Scandinavia), the nature of the rock overlying the host rock has major significance for safety. In fractured crystalline rock extending to the surface, the possibility of fast pathways (e.g. connected fractures linking through to the near-surface) existing, either at the present time or at some time in the future can undermine the performance of the geosphere barrier. Strata overlying the host rock should therefore either severely retard radionuclide migration (through restricted groundwater flow and/or superior sorption properties) or act as a medium to greatly disperse and dilute the repository-derived concentrations. The principal rock types that show these properties are plastic, self annealing ‘soft’ clay formations and halites, for low permeability and retardation properties; and sandstones and some types of permeable limestone formations, e.g. Chalk, for facilitating dispersion/dilution. Regional groundwater conditions should be such that high hydraulic gradients are unlikely to be developed.

The prime geological selection criteria applied during a regional study to select potentially suitable areas, or discount unsuitable areas, are therefore likely to include:-

- Identification of a suitable host rock at an appropriate depth (e.g. crystalline rock or indurated mudrock).
- Presence of overlying strata of reasonable thickness that supports the geosphere barrier or dispersion/dilution function (where an overlying rock unit different from the host rock is judged a suitable concept).
- Limited structural complexity that is either already well known and that would consequently not prohibit further investigation, or that is less well characterised than elsewhere but which may nevertheless be potentially suitable.

- Regional hydrogeological conditions that indicate that a comprehensive investigation would be possible, using standard techniques and in a reasonable timeframe.
- Restricted presence of known or indicated exploitable mineral or groundwater resources.

Consideration of socio-political factors that would influence selection are discussed in more detail by Barker and Hunt and environmental factors would also need to be evaluated.

The work involved at this stage would comprise the construction and population of a Geographical Information System (GIS*)* for the UK. It is known that Leeds University have already developed a GIS model and database for radioactive waste disposal purposes. BGS and the Environment Agency (EA) have their own in-house GIS's in place. Therefore a Nirex GIS database would probably mean the enhancement of existing GIS models, rather than the construction of a new one from scratch. The project GIS would be the principle tool for comparing and evaluating regions. The component modules within the GIS would have datasets that include:

- Regional scale topography
- Surface geology (lithological, structural) based on 1:50,000 mapping of Drift and bedrock exposure.
- Sub-surface geology (lithological, structural)
- Regional geophysical information (gravity, magnetics etc)
- Regional geothermal gradients
- Hydrogeology (hydro-units and piezometric surfaces)
- Borehole database
- Mapped mineral resources
- Hydrology (Rivers, springs and near-surface water catchments)
- Hazards (flooding potential, landslip activity, contaminated land)
- MORECS meteorological information
- Towns, cities and arterial transport links
- MOD land ownership

All of the above information already exists, and most of it is available in digital formats. The main call on resources will therefore involve the compilation and organisation of the various datasets and the use of expert judgement to decide on suitable regions for more detailed consideration. Effort should also be made to make the information clearly presentable (e.g. via a website and by using simple and accessible publications).

This initial part of the Stage 1 geoscience investigations would likely last 12 months. Nirex would carry the study out primarily in collaboration with the British Geological Survey (BGS) and, providing there are no conflicting issues regarding independence, with specialist units within the Environment Agency (EA). Detailed cross-checking of information would be advisable at several stages by the involvement of key university Earth Science departments in the different regions. This would engage a broad spectrum of people, thus ensuring that ongoing work is kept clearly in the public arena and that conclusions are properly scrutinised at all times by suitably qualified peers.

A principal consultant would be chosen to lead Stage 1 (probably the BGS) with at least three full time technical staff involved for 12 months in enhancing the existing BGS GIS and loading it with additional data to create a system specifically created for radioactive waste site investigation purposes. Senior BGS staff from a number of disciplines (structural geologists, geophysicists, hydrogeologists, mineralogists etc) would contribute a total of ca. 12 man months effort to provide interpretations of the information in close collaboration with Nirex. The equivalent of two man years effort by external agencies should be assumed for them to provide supporting information and contribute to interpretation in the context of radioactive waste disposal. Two man months effort from senior staff in up to 10 universities would be required to provide local regional supporting information and to act in a review capacity. It is not anticipated that there would be a significant call on the resources of commercial organisations at this stage. In collaboration with Nirex, BGS and EA staff, a body of experts (the expert panel) would undertake an ongoing appraisal of the GIS output and the investigation plans. In addition to a review function, they would provide the supporting material for a set of recommendations to be forwarded by Nirex (or its successor) to a radioactive waste policy or review board. One man month effort per panel member over the period of 12 months should be assumed.

The costs for this initial phase of Stage 1 are estimated as follows:-

ITEM	COST (£k)
GIS Hardware/Software and website enhancement	150
BGS Staff time for data compilation and interrogation	350
BGS Staff time for data interpretation	170
EA, Met Office etc staff time for compilation & interpretation	200
University staff time for data compilation and review	300
Expert decision and review group	100
Publication, review costs and responses	150
TOTAL	£1.42 million

NB.

It is not expected that Nirex would have to pay a premium to support costs already incurred by the BGS and other public bodies in developing their existing databases.

Typical present day BGS staff and other consultant costs have been used, plus a 50% component for overheads.

It is anticipated that up to 6 broad regions might be chosen for more detailed study. The next step, therefore is to identify Districts of size 400km^2 to 2500 km^2 (e.g. 20x20 km to 50x50 km) which show promise worthy of further, yet more detailed, consideration in Stage 2. This is likely to be a continuation of the largely desk-based studies, although restricted site investigations involving limited field studies using non-intrusive techniques might be necessary.

The objective of this part of the Stage 1 study would be the identification of areas that provide relatively consistent geological and environmental conditions, i.e. that suggest a degree of homogeneity that might in turn suggest relatively easy detailed interpretation and confidence in such interpretations. The GIS would remain the principal tool for collating and interrogating the data. The datasets collected during Stage 1 would be augmented by new information and a more complete consideration of existing information in the GIS, but investigated at finer spatial resolution. New datasets which could be added to the earlier Stage 1 GIS database might include e.g.

- Remote Sensing data (multispectral, hyperspectral, radar)
- Consideration of available seismic exploration survey data (reflection and refraction)
- Information on local stress fields from existing data sources
- Review of groundwater data (hydraulic and hydrochemical) from borehole records
- Individual river catchment water fluxes and balances based on available data
- Surveys (mainly desk-based) of land use, e.g. industrial and residential areas, Sites of Special Scientific Interest, archeological sites, wildlife reserves, land use etc. to produce 'conservative' boundaries that limit areas of the Districts from further consideration.

The coarse scale investigation of data already in the GIS would be supplemented by finer resolution detail from e.g.

- Airborne Geophysical Surveys (gravity, magnetics, infra-red)
- More detailed scrutiny of geological and hydrogeological characteristics (1:10,000 map analysis).

Because the decisions taken at this stage will probably be significant refinements of the earlier Stage 1 investigations, but will still be quite generalised, the time taken for compilation and interpretation will probably be equal to Stage 1 (a further for 12 months acquisition and interpretation).

The costs are estimated as follows:

ITEM	COST (£k)
Limited airborne surveys and purchase of data	1,500
BGS Staff time for data compilation	150
BGS Staff time for further data interpretation	250
EA & Met Office staff time for compilation & interpretation	100
University staff time for data compilation and review	100
Expert decision and review group	50
Publication, review costs and responses	150
TOTAL	£2.3 million

The results of social/political considerations in any contemporaneous Stage 1 multi-attribute decision analysis (costs not included) would be refined and taken forward to be used in conjunction with the geoscience evaluations. It is anticipated that between 6 and 30 Districts in up to 6 regions could be identified in Stage 2 as geologically worthy of further study, but from a logistical perspective it is likely that a maximum of 10 Districts would be taken forward for stage 2 studies. The criteria for reducing the shortlist at this stage and the decisions would have to be made by others. Such decisions may well ultimately rest on non-technical criteria. The key deliverable from Stage 1 would be a GIS and a report providing the background, the methodology and the results from the study. It would also include the recommendations for the Regions and Districts judged suitable for more detailed consideration in stage 2.

5.2 Stage 2: Identification of Potentially Suitable Sites

Within each of the identified Districts, one or more Sites will be evaluated for more detailed consideration in stage 2. This will therefore entail an extension of the knowledge gained from the identification of Districts. It will likely comprise further desk-based studies using yet more detailed information, but at this stage new non-invasive investigation techniques will probably be used at a number of Sites and possibly some exploratory borehole drilling will be required if pre-existing boreholes are not present. The high level objectives at this stage are to (a) allow detailed but provisional conceptual models to be constructed; (b) provide data that will allow fair comparisons to be made between the different Sites on the basis of geological and hydrogeological interpretations, together with evaluations of the surface environment.

Each Site to be considered will probably have an area in the order of $<100km^2$ and there may be two or three such areas that require similar levels of investigation within each District. It is at this stage that more detailed consideration should be given to specifying the parameters that will be important for performance and safety assessments, together with acceptable uncertainty assignments and a methodology for dealing with such uncertainty.

5.2.1 Investigation objectives

- A good appreciation of the broad 3D geology (lithologies and structure) to at least potential repository depths (ca 500m) from results of surface mapping and 2D seismic, gravity and resistivity survey interpretations. Consideration should be given to drilling at least one borehole to 400 or 500m depth at each site where one does not already exist in order to obtain rock cuttings and possibly limited and targeted core samples (at least to potential host rock depths). Modern, multi-parameter geophysical logging of new or pre-existing boreholes (where they are present) should support interpretations of surface based surveys.
- For near-surface lithologies in which structures are difficult to resolve using seismic methods, remote sensing analysis and surface investigations (e.g. surveys to identify deep generated gas emanations or simply geomorphology) should be carried out to identify potential fault zones and their likely significance.
- Interpretation of indicative fracture frequency and flowing feature frequency from borehole geophysical logs, flow meter surveys and outcrop mapping.
- The nature of the local rock and hydrogeological properties making up the key lithological and hydrogeological units (vertical/horizontal permeability, hydraulic gradients, porosity, geotechnical moduli, sorption characteristics), based on discrete measurements from limited hydrogeological testing in boreholes with

isolated intervals at varying depth (either new or preferably pre-existing boreholes) and laboratory analysis of cuttings and targeted core samples. For near-surface hydrogeological investigations, shallow boreholes could be considered as they can be drilled without coring by simple but cost effective percussion methods.

- Construction of gross trends based on the rock and hydrogeological properties, extrapolated in line with scientific understanding and the 3D geological/hydrogeological model.
- Groundwater and surface water composition (concentrations of major elements, trace elements), limited isotopic studies to evaluate likely groundwater residence times.
- Walkover survey and collation of local knowledge concerning detailed land use, vegetation and representative crop types for agricultural land
- Soil composition using existing information
- Walkover survey and collation of local knowledge concerning detailed hydrological characteristics and meteorological information using available information.
- Construction of a conceptual model that will describe potential flowpaths at depth and the likely degree of heterogeneity in the studied geological environment.

5.2.2 Investigation methods

The stage 1 GIS will contain a wealth of relevant data and it would be augmented in stage 2 by data from non-invasive investigations and possibly data derived from borehole-based investigation methods. Laboratory studies of rock and water properties would also be carried out, together with the application of techniques to allow the identification of mineralogical episodes and groundwater evolution. Surface investigations (e.g. hydrology and meteorological conditions) would largely be designed to supplement data already held on the GIS. These various investigation methods are detailed in the following tables, together with the associated parameters of interest. The costs provided in the tables are based on investigations at a single representative site and cover both acquisition and interpretation activities.

ACQUISITION

General Investigation Objective	Investigation Method	Cost (£k)
Geological Model	2D seismic (total 15 km line length)	150
	Lithologic data acquisition (wireline, outcrop, limited core, rock cuttings)	20
	Ground based gravity and resistivity surveys	50
Fracture densities and geometry	Geophysical logging of boreholes and data processing	40
	Surface fracture mapping	20

Hydrogeology	Drilling one narrow diameter (60-75mm) borehole to 400-500m depth with limited core.	150
	Basic hydrogeological testing in borehole	50
	Core analysis for permeability/porosity	20
	Flow zone logging	20
Hydrochemistry	Borehole sampling	20
	Spring and stream sampling	20
	Chemical analyses	80
Surface features	Remote sensing analysis	30
	Walkover surveys	20
	Ground penetrating radar	50
	TOTAL	740

NB. The above estimate includes costs for drilling one borehole to approximately 400-500m depth with a standard rotary rig, using dosed drilling fluids. Targetted core would be taken, and return rock cuttings would be analysed This borehole cost element would be reduced to £25,000 for a situation where a suitable pre-existing boreholes in the vicinity could be utilised after renovation. Given that the long-list of sites would possibly include 20-30 localities, it would probably not be necessary to include costs for drilling a deep borehole at each location. Costs for drilling shallow (50-100m) boreholes not included as these are typical agricultural borehole depths and costs would be minimal.

It would not be possible to extensively characterise the sites of interest using the above techniques. Expert judgement would be used to identify the areas where targeted data acquisition would be most useful.

In addition to the above acquisition activities, ongoing data collation from other sources and data interpretation will be necessary. This will include limited modelling studies to identify data weaknesses and provide on-going interpretations that result in consistent conceptual models. The associated costs are estimated as follows:-

INTERPRETATION

ITEM	COST (£k)
Seismic interpretation	375
Gravity, magnetic & resistivity survey interpretation	90
Geological synthesis and modelling	100
Integrated hydrogeological data assessment	150
Regional near-surface hydrogeological model	50
Maintain database	150
Surface environment description	60

Expert decision and review group	50
Publication, review costs and responses	150
TOTAL	£1.175

On the basis of the above estimates, the total costs for a single site are estimated at £1.915 million. Note however that extensive seismic surveys already exist over about 15-20% of the UK and some areas have accessible deep boreholes already drilled. Therefore, significant cost savings may be made at some sites.

The overall cost for Stage 2 investigations is based on a nominal 15 sites being investigated in sufficient detail to allow for fair comparisons between them, and that allow a short list of perhaps 5 to 10 sites being chosen for detailed consideration. From this short list it would be expected that between 2 to 5 sites could be recommended to be taken forward to stage 3 for detailed investigation, based on stakeholder agreement and technical criteria that indicate the sites could be considered superior in terms of promise with respect to radiological safety, compared to the others. Overall Stage 2 costs are estimated at approximately £28.725m

The time involved in Stage 2 investigations would likely be three years for up to 15 sites being studied simultaneously (comprising two years acquisition and interpretation, and one year post acquisition interpretation to allow the short list to be derived). This presupposes that there is sufficient manpower and equipment available. This is judged realistic if equipment and service personnel are to be split into at least three teams, each allocated five sites that they investigate using different methods in rotation, with synchronisation to ensure that no one site is left alone for an extended period of time. For 30 sites the time would at least be doubled, but would probably be more due to decreasing efficiencies.

5.3 Stage 3: Detailed Surface-Based Evaluation of Sites

Stage 3 would involve a technical and fully detailed evaluation of two or three identified sites. Each of the sites would have to be situated in their own District in order to ensure that a local ‘characteristic’ that might result in one site being disqualified would not have the potential to disqualify another. It is also likely that at least two distinct types of geological environment would have to be considered, and this is unlikely to be possible within the same District. Intensive studies will be required around a proposed repository location (ca 4km^2 area), but the exact repository location would not be fixed at the outset of Stage 3 characterisation studies. Stage 3 studies would also consider the hydrogeological system outside the proposed repository domain in great detail, but it would be largely within the confines of the already defined District area.

The objective in Stage 3 is to fully characterise a site from the surface to provide sufficient information to support a preliminary safety case and to allow the completion of a comprehensive environmental assessment of the impacts of constructing a research facility and/or a repository underground. The Stage 3 investigations would also identify a potential volume of rock to provide on-going assurance that the construction of a repository was feasible and within acceptable design and cost constraints. Information from Stage 3 would be used to allow a decision to be made concerning whether or not the construction of a research facility underground was required in order to better characterise the three dimensional attributes of the geosphere and repository environment. Such a facility would further test assumptions regarding construction feasibility and radiological protection. Alternatively, it might be judged that sufficient information exists from surface-based characterisation to allow a proposal for a repository to be submitted and research on detailed underground characteristics could form part of the initial repository construction phase.

Detailed surface-based site investigation costs are uncertain, due to the inherent uncertainty in the nature of the sub-surface environment at a particular site. Unexpected ground conditions should be anticipated anywhere and contingencies made. The following cost evaluation and outline programme presupposes straightforward investigations that collect the appropriate data at a sufficient level of detail in the first instance.

Most effort should be made towards evaluating the nature of potential pathways for fluid movement through the rock mass and measuring those characteristics that affect the transport of radionuclides (mineralogy and geochemistry/hydrochemistry). In this respect the level of detail needed from the investigation programme will be predicated by the needs of the assessment analyses and regulatory considerations. However, there will also be certain expectations concerning surface and near-surface information that would need to be collected in order to demonstrate that the present day surface environment around the site is fully understood, even though some of the present day near-surface and surface conditions will have little significance for possible radionuclide discharges far into the future. Current environmental parameters will be required, however, for a full environmental assessment.

Nirex 97 provides a good basis for a compilation of parameters that are likely to be necessary for safety assessments. The following are the key features of interest:-

Main Dataset	Feature (parameter)	Acquisition Method
Geological	Topography	Digital terrain model from OS and site survey
	Lithological Units	Seismics, core and outcrop mapping
	Folding and faulting (gross geometry)	Seismics and outcrop mapping
	Fault zone characterisation (orientation, width, length, displacement direction, displacement direction and displacement history).	Seismics, outcrop and modelling
	Sedimentary architecture	Outcrop, core, seismics, analogues
	Mineralogy and diagenesis (composition, evolution, fabric)	Outcrop and core sample analyses
	Fracture characteristics (density, orientation, connectivity)	Borehole logging, outcrop mapping, core analysis

Hydrogeology	Groundwater environmental pressure (and its spatial variation)	Borehole testing and monitoring
	Water table levels across the area	Borehole monitoring
	Freshwater head calculation	Borehole testing and monitoring
	Environmental head calculation	Borehole testing and monitoring
	Permeability (horizontal, vertical)	Borehole testing, core analysis, geophysical techniques (NMR, electro-kinetic sounding)
	Porosity (total, interconnected, effective)	Core analysis, wireline logging
	Storage coefficient	Borehole testing, core analysis
Flowing Feature Characterisation (both present day and potential)	Flowing feature density, length, orientation, connectivity, effective hydraulic aperture	Flow logging, borehole testing and geophysical logging
Radionuclide transport	Sorption potential (Kd)	Tracer tests and laboratory analysis
	Break through times	Tracer tests
	Flow wetted surface	Field tests and laboratory analysis
Hydrochemistry	Eh, pH	Borehole sampling, spring and stream sampling and laboratory analysis
	Major and trace element concentrations	Borehole sampling, spring and stream sampling and laboratory analysis
	Dissolved gases	Borehole sampling, spring and stream sampling and laboratory analysis
	Groundwater and environmental Isotopic analysis	Borehole sampling, spring and stream sampling and laboratory analysis

	Colloidal composition	Borehole sampling, and laboratory analysis
Microbiology	Bacterial concentrations and species	Groundwater analysis
Thermal	Thermal gradient	Borehole measurements
	Thermal conductivity	Laboratory analysis of core
	Heat capacity	Laboratory analysis of core
Rock mechanics	Co-efficient of thermal expansion	Laboratory analysis of core
	Compressibility and strength in different stress directions	Laboratory analysis of core
	Q and RMR (rock strength criteria)	Laboratory analysis of core
	Young's modulus	Laboratory analysis of core
	Poisson's ratio	Laboratory analysis of core
	Rock density	Laboratory analysis of core, seismics
	In situ stress	Overcore, breakout and hydro-frac in borehole
Surface environment	Meteorology (precipitation, temperature, wind speed and direction)	Automated weather station(s)
	Stream flows and characterisation of influent/effluent areas	Stream gauges and monitoring
	Spring flows and temperature of discharge waters	Spring monitoring
	Soils (thickness, type, hydraulic conductivity, matric potential)	Surveys
	Pre-existing background radiation levels.	Surveys
	Natural fauna	Surveys
	Vegetation (natural and arable)	Surveys

Combinations of some of the above parameters will provide other parameters of interest (e.g. knowledge of fluid salinity from groundwater chemical compositions and the fluid temperature will allow fluid density to be derived, which is itself required for environmental head calculations, or hydraulic diffusivity can be derived from knowledge of permeability and storage coefficient). The above list is not exhaustive, but is considered to contain the main parameters of interest for a safety assessment and to allow detailed repository design. Many of the measurements will be ‘one-off’, whilst others will be regularly monitored. A ‘Baseline’ dataset of regularly monitored parameters will need to be established at an early stage. The requirements and rational for baseline monitoring will need to be established in advance.

In some cases, measurements will have to be made on several length scales in order to provide a proper representation of the application of the data in various models (and to assist in upscaling other parameters).

There are a number of reasons why the above parameters should be collected, but one of the most important reasons is to provide confidence in the developing conceptual model of the site and supporting repository design efforts. Some of the parameters will assist in interpretations in more than one area (e.g. porosity has implications for groundwater flow, radionuclide transport and can also contribute to a proper understanding of rock strength, which is required in repository design).

In addition to the acquisition and interpretation costs, there will also be a need to invest in a robust and comprehensive data management system (database). This will have to be designed specifically to incorporate the complex multi-disciplinary data generated at each site, some of which will change with time. This poses severe challenges for such a major programme, but there is now a great deal of experience within Nirex in commissioning and running such database systems.

In order to ensure cost effectiveness, while meeting the requirement to address issues to satisfy a wide audience, there will be a need to establish a decision-making framework to identify the sufficiency of data that is required for safety assessments. This will mean agreeing *a priori* the levels of parameter uncertainty that can be effectively dealt with. The continued collection of some types of data may compromise the potential stability (in a radiological protection sense) of a particular site as any invasive investigation disturbs the disposal system. Decisions will need to be made concerning ‘when is there enough data’ to satisfy scientific debate. Prior to completion of Stage 3 investigations at each site, a review of when sufficient data has been collected will be necessary.

The following is an outline evaluation of costs for an 8 to 16 year programme of site characterisation at a single site.

ACQUISITION

General Investigation Objective	Investigation Method	Cost (£k)
Seismic survey	3D seismic survey (total 25 km^2 area with meter scale resolution to 2 km depth)	10000
	2D seismic refraction line, 10km total line length to 10km depth	500
Borehole Drilling and Related Activities	Cored deep vertical or inclined boreholes (5 in number, one to 1500m depth, others to 1000m)	15000

	Deviated (to horizontal) boreholes (2 in number, horizontal at potential repository depth and up to 2000m length)	10000
	Additional vertical or inclined deep boreholes for hydrochemistry and groundwater pressure monitoring (15 in number)	7500
	Cored shallow boreholes, 100-200m depth (10 in number)	2000
	Additional non-cored shallow boreholes (percussion) for pressure monitoring (10 in number)	500
	Geodesy – surveying borehole locations and trajectories	320
	On-site core analysis	5000
	On-site hydrochemical analysis	5000
	Hydrogeological testing during borehole drilling for 20 deep and 20 shallow boreholes	2500
Surface-based geological surveys	Detailed surface mapping – Quaternary and bedrock geological formations, meso-scale structures and fracture populations	500
	Detailed surface mapping – Sedimentary architecture and crystalline rock fabrics as analogues for rock at depth	100
	Detailed surface mapping – Review of fault characteristics for neotectonic structures as part of seismic hazard assessment	50
	Seismic monitoring installation and maintenance over 10 years based on 5 surface stations in region.	500
	Geophysical land-based surveys, e.g. GPR, resistivity, electrokinetic, magnetic and electromagnetic, CSAMT etc	2500
	Geophysical air-based surveys, e.g. magnetic, radiometric, gravity, infra-red.	300
Stress Measurements in boreholes	Over-coring and hydrofracturing in 10 boreholes	50
Post-Completion Borehole Investigations (geophysics)	'Standard' Geophysical logging of all boreholes (e.g. caliper, gamma, neutron, resistivity, sonic, BHTV etc).	5000

	Vertical Seismic Profiling	100
	Cross-hole tomography from 4 boreholes	100
	Borehole radar in 10 boreholes	100
	Nuclear Magnetic resonance logging	200
Post-Completion Borehole Investigations (hydrogeological)	Post-completion short-term hydrogeological (hydraulic) testing in deep boreholes	2000
	Post-completion hydrogeological (hydraulic) testing in shallow boreholes	200
	Installation of pressure/groundwater sample monitoring strings in 25 deep boreholes (average 10 probes per borehole string + spares)	2500
	Installation of data loggers in 20 shallow boreholes	40
	Telemetry network	2000
	Post-completion long-term hydrogeological (hydraulic) testing in one deep borehole	1000
	Hydrogeological (Tracer) test in deep boreholes (forced gradient)	50
	Hydrogeological (Tracer) testing in shallow boreholes (natural and forced gradient)	100
	Flow zone logging (POSIVA – type flow meter)	1000
Other hydrogeological investigations	Core analysis for permeability/porosity (ca. 1000 samples)	50
	Core analysis for fractures and potential flowing features ('recent' mineralogy), includes SEM, fluid inclusion studies, CL.	2500
	Core analysis for sedimentary architecture	50
Hydrochemistry & Geochemistry	Off-site laboratory analyses – groundwater trace & major elements	4000
	Off-site laboratory analyses – groundwater isotopes	1000
	Whole rock analysis (XRF, XRD)	100
	Mineralogical analysis (geochemical & isotopic)	2000
	Groundwater and mineral radiometric dating	3000
	Spring and stream sampling & analysis	30

	Rainfall sampling & analysis	10
Rock Mechanics	Laboratory testing of samples	2000
Thermal property Evaluation	Laboratory testing of samples	500
Hardware	Essential equipment (vehicles, maintenance equipment for engineering workshops) spares and computing facilities)	5000
Surface features	Walkover surveys – land use	20
	Walkover surveys –hydrology	50
	Hydrological and meteorlogical network comprising 10 gauging locations and 5 AWS	200
	Natural background radiation survey	50
	TOTAL	97.270 (£97.27m)

NB Costs for land purchase and buildings, land access and permissions are all additional.

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INTERPRETATION

ITEM	COST (£k)
Surface geology and bedrock interpretation from surface mapping and remote sensing / aerial photograph interpretation	500
Seismic interpretations and earthquake focal plane analysis from seismic network	6000
Integrated geological modelling (back-stripping evolutionary model, 3D geological models on various scales)	1000
Hydrogeological test analysis	5000
Groundwater monitoring analysis and cyclic fluctuation interpretations over 10 years	1000
Stochastic model for potential flowing features and permeability distributions	2000
Regional near-surface groundwater, meteorological and hydrological interpretations over 10 years	500
3D groundwater flow and transport models (incorporating deep DFN and CPM models for current conditions at site, evolutionary regional model near-surface CPM)	10000
Geochemical interpretations	10000

Mineralogical and lithological interpretations	5000
Rock mechanics interpretation	2000
Thermal data interpretations	100
Design and management of Central Geoscience Database*	5000
Publication costs	5000
Expert review Group	2000
TOTAL	55,100 (£55.1 million)

*NB * The geoscience database costs are estimated at 500,000 per year per site for an illustrative period of 10 years.*

The overall costs for a single illustrative site are estimated to be ca. £152m.

6 COST SUMMARY

Stage 1: Identification of Regions and Districts

Objectives: Review regional scale geological environments across the UK and identify areas that provide relatively consistent geological and environmental conditions on a District scale.

Criteria:

- Identification of a suitable host rock at an appropriate depth.
- Presence of overlying strata of reasonable thickness that support the geosphere barrier or dispersion/dilution function.
- Limited structural complexity that is either well understood and that would consequently not circumvent further investigation, or that is less well characterised than elsewhere but which may nevertheless be potentially suitable.
- Regional hydrogeological conditions suitable for more detailed characterisation.
- Restricted presence of known exploitable mineral or groundwater resources.
- Consideration of socio-political factors discussed in more detail by Barker and Hunt.

Total Stage 1 technical costs: £3.72m

Stage 2: Identification of Potentially Suitable Sites

Objectives: Identification of Site scale areas within the Districts chosen from Stage 1 evaluations. Stage 2 work will be directed towards providing (a) detailed but provisional conceptual models and (b) sufficient data that will allow fair comparisons to be made between the different Sites, on the basis of geological and hydrogeological interpretations, together with evaluations of the surface environment

Criteria: In addition to continuing adherence to Stage 1 criteria,

- Geological environment that allows construction of well supported geological models based on fully defined lithological units and structural components.
- Continuing evidence for hydrogeological conditions at repository depths indicative of low flow (low driving forces and low permeability).
- Groundwater chemistry that is consistent with conceptual models and would not significantly reduce or adversely affect repository or geosphere safety functions.
- Host rock strength and fracture properties that would be suitable for repository construction and long-term stability.
- Surface conditions that would not cause undue problems in an environmental assessment

Total Stage 2 technical costs: £1.915m per site. For 15 sites = £28.725m

Stage 3: Detailed Surface-Based Evaluation of Sites

Objectives: The objective in Stage 3 is to fully characterise a site from the surface in order to provide sufficient information to support a preliminary safety case and to allow the completion of a comprehensive environmental assessment of the impacts of constructing a research facility and/or a repository underground. The Stage 3 investigations would also provide on-going assurance that construction of a repository was feasible and within acceptable design and cost constraints. Information from Stage 3 would be used to allow a decision to be made concerning whether or not the construction of a research facility underground was required in order to further characterise the three dimensional attributes of the geosphere and repository environment. Such a facility would further test assumptions regarding construction feasibility and radiological protection. Such a research facility could be considered as a follow on from the investigation programme outlined here, or as the first stage of a repository programme. Because of the implications for such a major decision and the need to thoroughly evaluate technical proposals for work to be carried out in an underground laboratory, cost estimates for underground investigations have not been included in this note.

Outline Criteria: To be specified, but relate to satisfactory accomplishment of objectives.

Total Stage 3 technical costs: £152.37m per site. For 3 sites = £457m

Overall estimate of technical programme costs: £491m.