APP/H0900/A/94/247019

APPENDIX 1 TO INSPECTOR'S REPORT

CUMBRIA COUNTY COUNCIL

APPEAL

by

UNITED KINGDOM NIREX LIMITED

ASSESSOR'S REPORT

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12 November 1996

To Mr C S McDonald MA DMA LMRTPI Solicitor
Inspector

Sir -

1. It was my honour to be appointed Assessor to advise you in considering matters relating to geology and hydrogeology raised in connection with the appeal by United Kingdom Nirex Limited into refusal of planning permission for the construction of a Rock Characterisation Facility at Longlands Farm, Gosforth, Cumbria. I am now pleased to present to you my report.

2. I sat with yourself and the Assistant Inspector during the greater part of the Inquiry, during which the technical and scientific issues concerning the RCF proposal and related deep radioactive waste repository were presented and examined. I have considered the oral evidence together with the very numerous inquiry documents and written representations relevant to my area of interest.

3. The Secretary of State had previously indicated a number of matters on which he particularly wished to be informed in considering the appeal, of which Matter 6 concerned 'The results available so far from studies and surveys of the geology and hydrogeology of the area; the additional information that might become available from the RCF, if developed; and the benefits to be gained from obtaining that additional information, if any, weighed against the possible impact the RCF might have on the site and surrounding area'. My appointment was intended to advise you on the results, additional information, and benefits in question, and any related scientific and technical matters.

4. The arrangement of this report reflects the matters on which you specifically asked me to advise. The observations and opinions are, of course, entirely my own. Very many interesting and important scientific and technical issues were raised during the inquiry and generated a large amount of evidence. I trust that I have given adequate explanation and comment on those that are particularly relevant to the decision on the planning merits of the current development proposal and within my field of expertise.

5. The task has been interesting and stimulating. I thank you and the Assistant Inspector for your help and encouragement during the inquiry and subsequently.

ABBREVIATIONS AND ACRONYMS

Parties

Construction Workers	=	Cumbria Construction Workers
Copeland	=	Copeland Borough Council, the district planning authority
CORE	=	Cumbrians Opposed to a Radioactive Environment
Cumbria	=	Cumbria County Council, the respondent planning authority
FOE	=	Friends of the Earth Ltd
FOE Cumbria	=	Cumbrian Groups of Friends of the Earth
FOLD	=	Friends of the Lake District, the local branch of the Council for the Protection of Rural England
GAG	=	Gosforth Action Group
Gosforth	=	Gosforth Parish Council, the parish council
Greenpeace	=	Greenpeace Ltd
HMIP	=	Her Majesty's Inspectorate of Pollution
Nirex	=	United Kingdom Nirex Ltd, the appellant company
NSCNFLA	=	National Steering Committee of Nuclear Free Local Authorities
Shop Stewards	=	Windscale & Calder Joint Shop Stewards Committee
SCC	=	South Cumbria Citizens, a coalition of interested persons

Other Acronyms & Technical Terms

(NB Orders of magnitude are generally expressed according to the normal scientific convention, eg:- 10^8 = a hundred million & 10^{-6} = a millionth or one in a million)

ACSNI	=	Advisory Committee on Safety of Nuclear Installations
ALARA	=	as low as reasonably achievable
aOD	=	above Ordnance Datum
BGS	=	British Geological Survey

BH	=	borehole
BNFL	=	British Nuclear Fuels plc
bOD	=	below Ordnance Datum
BPEO	=	best practicable environmental option
Bq	=	becquerel(s)
BUSC	=	basement (rock) under sedimentary cover
BVG	=	Borrowdale Volcanic Group (of rocks)
CDF	=	Cumulative Density (Distribution) Function
cm	=	centimetre(s)
COMARE	=	Committee on Medical Aspects of Radiation in Environment
cu	=	cubic
DSA	=	Detailed Safety Assessment
DWR	=	deep waste repository
ECJ	=	European Court of Justice
ES	=	Environmental Statement
FHFZ	=	Fleming Hall Fault Zone
F<no.>	=	Fault <number>
Green Book	=	Disposal Facilities on Land for Low & Intermediate-Level Radioactive Wastes: Principles for the Protection of the Human Environment 1984 [Doc.GOV/302]
g	=	gram(s)
ha	=	hectare(s)
HLW	=	high-level, or heat-generating, (radiaoctive) wastes
IAEA	=	International Atomic Energy Agency
ICRP	=	International Commission on Radiological Protection

ILW	=	intermediate-level (radioactive) wastes
k	=	kilo
LDBFZ	=	Lake District Boundary Fault Zone
LLW	=	low-level (radioactive) wastes
LP	=	Copeland Local Plan, deposit version as recommended to be modified
M	=	million(s)
m	=	metre(s), or as first letter in compound abbreviations = milli-
MADA	=	multi-attribute decision analysis
MASCOT	=	program of suite of sub-models to quantify radionuclide flow from repository to biosphere
NAMMU	=	groundwater modelling program of the continuum porous medium type
NAPSAC	=	groundwater modelling program of the fracture network type
NEA	=	Nuclear Energy Agency (of the OECD)
NII	=	Nuclear Installations Inspectorate
NRPB	=	National Radiological Protection Board
NRVB	=	Nirex Reference Vault Backfill
NSARP	=	Nirex Safety Assessment Research Programme
OECD	=	Organisation for Economic Co-operation & Development
pa	=	per annum *[and see /y below]*
PCPA	=	Post Closure Performance Assessment
PCRA	=	Post Closure Risk Assessment
PCSA	=	Post Closure Safety Assessment
PCSR	=	Pre-Construction Safety Report

PDF	=	Probability Density or Distribution Function
PERA	=	Preliminary Environmental & Radiological Assessment [Doc.COR/501 - Nirex Report No.71]
PRZ	=	potential repository zone, the main part of the appeal site
PSA	=	Probabilistic Safety or Systems Assessment
RADWASS	=	(IAEA's) Radioactive Waste Safety Standards Programme
RCF	=	rock characterisation facility
RCM	=	rock characterisation monitoring (boreholes)
REV	=	representative elemental or elementary volume (of rock)
RSA	=	Repository Safety Assessment
RWMAC	=	Radioactive Waste Management Committee
/sec	=	per second
SFZ	=	Seascale Fault Zone
SP	=	Cumbria & Lake District Joint Structure Plan 1991-2006, adopted July 1995
SSG	=	Sherwood Sandstone Group
STZ	=	Saline Transition Zone
Sv	=	sievert(s)
t	=	tonne(s)
TBq	=	Tera-becquerel (a million million - 10^{12} - becquerels)
TOR	=	Tolerability of Risk
URL	=	Underground Rock Laboratory (Canadian or Swiss)
VEM	=	Visual Envelope Map
/y	=	per year
ZLEC	=	zone of locally enhanced conductivity

A BASIC CRITERIA FOR REPOSITORY - GEOLOGICAL & RADIOLOGICAL

Preliminary

A.1 Over the past two decades or so, policy statements and technical, scientific and planning criteria have been developed at international, European and UK levels that are applicable when considering the selection and suitability of potential radioactive waste repository geological environments and specific sites in and deep below the ground.

A.2 Criteria can be prescriptive if they specify quantitative values that must be complied with, actions to be taken, procedures required to be followed, or systems that must be put in place. Conversely indicative criteria may lay down quantitative values or ranges that experience has shown to be generally appropriate in various circumstances, and actions, methodologies and systems that, if adopted, are likely to ensure a satisfactory outcome. This may include compliance with prescribed standards,

A.3 The legislative and regulatory framework prevailing in the UK is prescriptive in the general sense but its requirements may be more qualitative and of a general nature than specifically quantitative. Similarly guideline documents and codes of practice, whether national or international, can vary from general advice relating to model situations and therefore open to interpretation, variation or alternative approaches, to positive advice that would be applicable in most circumstances and which, whilst not having legal force, would be deemed to represent the best technical or professional practice and which would be strongly expected to be followed.

A.4 The evidence presented at the inquiry shows that, except for a few key radiological protection requirements, the legal requirements are expressed in relatively general terms but that the guidance documents issued by regulatory and advisory organisations contain detailed advice that a repository developer would be expected to follow.

Geological and Hydrogeological Criteria

A.5 About 20 years ago the Institute of Geological Sciences (now BGS) developed hydrogeological and hydrological criteria for deep burial options as part of the UK research programme into the feasibility of geological disposal of HLW [COR/615]. From the creation of Nirex in 1982 the organisation appears to have worked closely with BGS in its research into finding appropriate geological environments.

A.6 Most recently there has been the RWMAC/ACSNI report [GOV/409] on Site Selection for Radioactive Waste Facilities and the Protection of Human Health, published in March 1995. Although it is not appropriate to assess Nirex's previous site selection procedure against the report's recommendations in specific detail, aspects of the report concerning geological criteria to be used in site selection are discussed in paras.A.35-38 below.

A.7 There are also numerous international and European guidance documents relevant to the siting of deep radioactive waste repositories. A common thread can be seen in the key criteria expressed in the various guidance documents, and a number of other factors are frequently mentioned but given less emphasis.

A.8 Although each site must be considered on its own merits, and some factors and processes may be highly site specific and interactive, the documents take the view that it is possible to itemise general factors governing the suitability of a repository location. [GOV/501, s.6; GOV/507, para.401] However they caution that although the geological environment should have appropriate features, a common view is that it should not be considered in isolation, on the grounds that appropriate engineered features could permit sites which satisfy certain minimum requirements to be developed to accept a wide range of wastes. [GOV/502, s.5.1] The international approach to deep geological disposal is based on the multi-barrier concept in which the safety of a disposal system does not rely on one single component or barrier but on the combined performance of several barriers. Nevertheless the principle underlying a policy of deep, as opposed to shallow, underground disposal must be that the geological barrier is expected to play a leading role in the radiological safety performance.

A.9 Adequate size of site: What might be regarded as a self-evident truth is that the depth and dimensions of the host rock should be sufficient for hosting the repository [GOV/507, para.405] as well as providing an adequate subsurface buffer volume and an appropriate surface exclusion area [GOV/502, s.5.1.1]. The appropriate dimensions of the host rock will depend on the option, the waste to be disposed of, the repository capacity and the geological settings. The formation should have a sufficient depth and be large enough to provide an efficient isolation of the repository from the biosphere. The depth of the repository should be sufficient to take into account erosion of the ground surface, and there should be no possibility that the wastes could be exposed to the biosphere until the radionuclides have decayed to insignificant levels [GOV/501, p.22].

A.10 There is no specific definition of the term 'deep'. It is merely intended to emphasise the distinction between mine-like disposal facilities and those for near surface disposal [GOV/507, para.110]. On the other hand there are practical limitations to depth: Nirex has identified mining and geotechnical, waste storage and chemical reactivity problems of going too deep, as a result of increasing temperatures and confining rock stresses

A.11 Characterisability/predictability: A criterion expressed in every guidance document, usually ranked first or second in running order, is an expression of the need for or advantage of being able to characterise the geology and predict the behaviour of the geological and hydrogeological system.

A.12 As early as 1976 the Institute of Geological Sciences' report on relevant geological criteria for deep underground disposal of HLW in the UK advised that the hydrogeological conditions should be simple and determinable, so that forecasts of possible routes from the burial site to the surface and acceptable predictions of transfer times can be made. [COR/615, criterion 3.2] This requirement was explained in the introduction to that section of the report: once solid waste material is buried or released beneath the ground it is circulating groundwater that presents the greatest risk of transporting derived wastes from the burial site back to the biosphere, so the disposal area should have characteristics that prevent such migration. Although written in the context of HLW I would say that the link between simple and determinable geology and confidence in prediction of flowpaths and travel times would also be relevant to any site proposed to house significant quantities of long-lived radioactive waste (which would include the IL/LL waste inventory considered at the RCF inquiry).

A.13 A 1983 IAEA document expressed the strong advice that it should be possible to characterise the properties of the host rock in the vicinity of the repository to such an extent that the performance of the repository can be effectively predicted [GOV/501, p.22 suitability factor (a)]. The 1994 IAEA report on repository siting [GOV/507, paras.404/5] said that the geological setting of a repository should be amenable to overall characterisation and have geometrical, physical and chemical characteristics that combine to inhibit the movement of radionuclides from the repository to the environment during the time periods of concern. Uniform rock formations in comparatively simple geological settings are preferred because they are likely to be more easily characterised and their properties more predictable. Similarly, formations with few major structural features or potential transport pathways whose impact on performance can be readily assessed are also preferred. The EC Euradwaste guidance document 1992 [NRX/14/2, s.III.1 - Hydrogeology] likewise stated that preference should be given to formations having high homogeneity and continuity and more generally showing simple patterns.

A.14 Hydrogeological characteristics of the rocks: The requirement for favourable hydrogeology is given similar emphasis in all guidance documents to that of geological characterisability.

A.15 The IAEA 1983 documents state that the hydrogeological characteristics of the geological environment should tend to restrict groundwater flow within the repository and, on a wider scale, that the hydrogeological characteristics of the host rock and the groundwater regime of the surrounding geological environment should favour waste isolation. [GOV/502, s.5.1.3; GOV/501, p.22 factor (b)] The 1992 EC Euradwaste and 1994 IAEA guides amplify the aspect of timescale by stating that the hydrogeological characteristics and setting of the geological environment should support safe waste isolation over the required time periods [GOV/507, para.412]; and ensure negligible radiological consequences on the site and at regional level under both normal and altered evolution scenarios. [NRX/14/2, s.III.1 - Hydrogeology]

A.16 Some of the more recent guidance documents mention diluting effects of groundwater. The 1992 EC document [NRX/14/2, ibid.] suggests that because water is the most effective natural carrier of radioactivity out of the repository, low ground water flow and/or appropriate dilution capabilities are essential requirements, together with appropriate characteristics of the underground waters. Similarly the IAEA guidelines on deep geological disposal [GOV/507, para.413] say that the dilution capacity of the hydrogeological system may also be important and should be evaluated (although this is qualified by saying that siting should favour long and slow moving groundwater pathways from the repository to the environment). I return to dilution in paras.A.33 & 34 below.

A.17 Gas: The 1994 IAEA guidelines [GOV/507, para.406] advise that depending on the potential for gas generation by the disposal system, the gas transport properties of the geological barrier should also be considered.

A.18 Avoidance of 'short circuit' pathways: 1983 IAEA guidelines [GOV/502, s.5.1.1] say that it is desirable that lithological contacts or mechanical discontinuities within the rock mass that serve as direct pathways or short circuits to the biosphere, should be far enough from the repository to permit the natural rock and engineered features effectively to impede the transport of radionuclides to these contacts, whereas the 1994 guidance [GOV/507, para.405] is that the depth and dimensions of the host rock should provide sufficient distance from geological discontinuities that could provide a rapid pathway for radionuclide transport. In either case the guidelines clearly envisage a substantial thickness of undisturbed host rock between the repository and the nearest geological features that represent significantly preferential pathways towards the biosphere.

A.19 Types of Host Rocks: The host rock and geological formations surrounding an underground repository represent the natural barriers within the multibarrier system. Their role is particularly important in relation to disposal of wastes containing long-lived radioelements. Although no one rock type is favoured, IAEA and EC reports describe international research as showing that salt deposits, clay sediments and granite formations are expected to offer adequate containment capabilities, and mention also igneous and metamorphic rocks in general, including tuffs, as being considered. [NRX/14/2 s.III.1; GOV/501 s.3.4; GOV/502 para.5.1.2] The IAEA general guidance is simply that a repository should be located in a geological medium with a lithology and depth appropriate for the categories and quantities of waste to be disposed of. [GOV/502, ibid.]

A.20 Geochemical factors: The principal IAEA and EC guidance documents each indicate that the physico-chemical and geochemical characteristics of the geological environment in general and of the host rock in particular should tend to limit the transport of radionuclides by favouring their retention. [GOV/501 p.22 factor (c); GOV/502 s.5.1.4; GOV/507 para.416; NRX/14/2, s.III.1 - Hydrogeol.] The choice of a host rock or a surrounding geological environment which has suitable retardation properties for the most radiotoxic and long-lived radionuclides is particularly important in the disposal of long-lived wastes. In formations where groundwater movement through fissures and pores occurs, retardation by minerals both within the rock matrix and on the fracture walls will be important to ensure satisfactory long-term performance of the repository system [GOV/502, ibid.].

A.21 The 1994 IAEA document on site selection [GOV/507, para.416] adds that the hydrogeological, as well as geological, environment should tend to limit the release of radionuclides from the disposal facility to the accessible environment, and is thus recognising the influence of hydrochemical reactions between repository porewater or leachate and groundwater.

A.22 Mechanical behaviour of the rocks: The mechanical properties of the host rock should be favourable for the safe construction, operation and closure of the disposal facility and for ensuring the long term stability of the geological barrier [GOV/507, para.406]. It may also be necessary for the rock to have appropriate thermal properties to ensure that any heat released by the waste is appropriately dispersed without impairing the confinement properties of the formation or induce undue heating of the overlying sediments and waters [NRX/14/2, s.III.1]. Disturbance of the site due to excavation of the repository should not impair its performance [NRX/14/2, ibid.] and the repository should be constructed so as not to endanger the hydrogeological isolation of the wastes [GOV/501, p.22 factor (e)]. In addition the mechanical behaviour of the rock should ensure that an appropriate sealing of the various repository areas and shafts can be achieved [NRX/14/2, ibid.].

A.23 Lack of resource potential: There is a need to minimise the risk of human intrusion, deliberate or inadvertent, into repository, particularly during the long period after closure. The siting of a disposal facility should be made with consideration of actual and potential human activities at or near the site. The most likely circumstance giving rise to such intrusion is considered to be the pursuit of mineral resources. Preference should therefore be given to geological formations having no great scarcity or economic value [GOV/501 p.22 factor (f); GOV/502 s.5.1.7; GOV/507 para.420], and specifically the EC guidelines [NRX/14/2, s.III.1] say that the formation should be located far enough from either ore deposits or minerals scarce enough to be considered as a possible object of future exploitation. Clearly with increasing depth, the risk of human intervention decreases, but metalliferous minerals, coal and evaporites are frequently mined at depths well in excess of say 1000m.

A.24 Geodynamic stability: It is common to all the guidance documents, and given a high priority, that a repository should be sited in a host rock and general locality that are not liable to be affected by future geodynamic phenomena (climatic changes, neotectonics, seismicity, volcanism, diapirism) to such an extent that these could unacceptably impair the isolation capability of the overall disposal system. [GOV/507, para 408]. The IAEA [GOV/502, s.3.2.2] says that confidence that disposal in deep geological formations is appropriate for HLW and alpha-bearing wastes (which would include long-lived ILW) is based on evidence that geological settings exist which have not undergone significant changes for major periods of geological time.

A.25 The factors of greatest concern are earth movements (tectonic activity) and seismicity, the latter being one consequence of the former, but less common incidents such as meteorite impact need to be considered. The EC guidance [NRX/14/2, s.III.1] requires that the risks due to catastrophic natural events which could, in a foreseeable future, deeply modify the present site conditions shall be analysed and shown to have a low probability of occurrence.

A.26 Early guidance was that areas devoid of major seismic activity will generally be acceptable even though they may be undergoing broad, regional uplift or subsidence, and that even areas affected by earthquakes may be acceptable provided the probability of an earthquake adversely affecting the rate of release of radionuclides can be shown to be acceptably small [GOV/502, s.5.1.5]. However the 1992 EC document Euradwaste 6 [NRX/14/2, s.III.1] gives more specific guidance than previously concerning tectonic movement, seismicity and volcanicity:
(a) It requires the site to present a high degree of stability, such that tectonic movement should not be expected to occur (or to induce significant phenomena) before, eg 10,000 years, evaluated at regional levels and forecasted from present trends and evidences of events in the past. More generally, the site should be deemed to be stable as long as necessary according to the safety assessment.
(b) Seismicity shall be low. Its acceptable level depends on the option and the site, but it shall be shown that tectonic movements are not expected to reach Level 7 of the Richter scale (or an intensity of IX-X in the modified Mercalli scale).
(c) The site shall be far enough, for example some tens of km, from geothermal anomalies or volcanic evidences.

A.27 Other stability factors: The location of the repository should avoid man-made and natural features, such as mine workings, caves and landslips, that could generate structural instability [GOV/502, s.5.1.6].

Utility of Geological Criteria

A.28 For the most part I do not disagree with the geological, geomorphololological and hydrogeological criteria that have emerged by international consensus to assist in the identification of areas and specific sites for deep radioactive waste repositories. Whilst some of the guidance documents principally concern high level wastes they associate these with other long-lived wastes and with alpha-bearing wastes. Since the UK ILW inventory being considered for deep disposal contains significant proportions of long-lived and ∀-generating wastes then the recommendations in such documents are clearly relevant in the present context. However, of all the criteria I consider that two principles are of overriding value: firstly that the site should be in a region of low hydraulic gradients, the corollary of which is that there should be slow-moving and long groundwater pathways; and secondly that the geology (and hence the hydrogeology) of the site and its surrounding district should be sufficiently uncomplicated as to be readily characterisable and predictable.

A.29 Since hydraulic gradients commonly reflect surface topography, low hydraulic gradients are likely to be associated with areas of low topographic relief. The less the driving force the lower will be the rate and amount of flow through the strata, so that the specific characteristics of the body of rocks and geological complexity have less influence on the behaviour of the groundwater system and are therefore less crucial. In such circumstances, diffusion and geothermal effects are likely to be more important factors than regional groundwater flow.

A.30 Relative simplicity or uniformity of the target geological environment is of great advantage because it would be expected to:
(a) lead to more confident selection of target areas at the desk study stages of site selection;
(b) lend itself to easier, less expensive field investigation, so reconnaissance investigations might be made at several straightforward localities for an equivalent cost and effort to that for a single geologically complex locality;
(c) there should be fewer lithological or structural or hydrogeological features to characterise and assign numerical values to, which in turn may lead to simpler models with fewer significant variables; and
(d) the physical, hydrogeological and chemical behaviour of the system should be more predictable.
The overall effect should be increased confidence in the data, increased confidence that all material parameters have been taken into account, and hence increased confidence in the eventual results.

A.31 As regards the quantitative criteria recently defined by the EC for geological stability of a repository site (see A.26 above), it is noteworthy that a period of 10,000 years is very short in relation to the half-lives of numerous radionuclides in the UK ILW/LLW inventory and in relation to the natural geological and climatic processes that have been considered during the inquiry. Similarly, although the requirement is that seismicity shall be 'low' these EC guideline figures would generally be regarded as equating to large earthquakes and severe surface effects. However the IAEA considers that in general, underground structures are less susceptible to seismic disturbance than surface structures and so waste will normally be safer underground than on the surface. [GOV/502, s.5.1.5]. I consider the timescale aspect to be unreasonably short and discuss it further in paras.E.71-85 below.

A.32 In fact the emphasis to be placed on any of the factors within the general heading of Geodynamic Stability is related to the timescale under consideration. Processes such as erosion and uplift, faulting and seismicity, climate change, and extreme events such as meteorite impact, assume much greater significance when considered over periods of tens or hundreds of thousands of years rather than merely hundreds and thousands, and even more so if a timescale of a million years or more is considered relevant. Having regard to the long-lived nature of a significant proportion of the wastes to be disposed of, a time horizon well beyond 100,000 years would appear to be appropriate wherever the potential repository site under consideration, and therefore close attention should be given to the probability of catastrophic and disturbing events and to the effects of gradual changes over such extended periods.

A.33 Recent EC and IAEA documents [NRX/14/2 & GOV/507] introduced into their Hydrogeological criteria the concept of dilution of radioactive contaminants in groundwater. This is a new concept compared with earlier guidelines and is relied on heavily by Nirex in the context of Sellafield. In particular Nirex acknowledges that in the long term some releases of long-lived radionuclides will inevitably occur and for mobile and long-lived radionuclides which do not appear to interact strongly with the host rock, such as chlorine-36 and iodine-129, dilution would be the most important process in reducing their radiological impacts. I find it somewhat surprising that dilution now finds some favour when, in the field of waste disposal generally, the 'dilute-and-disperse' principle has been superseded by that of containment.

A.34 In stressing the importance of dilution, Nirex claimed that similar conclusions have been reached in the NAGRA programme to develop a high-level waste repository in Northern Switzerland [citing NRX/13/3, p81]. However the geological setting is very different and the publication referred to says that large surface and near-surface water fluxes from the Alps and Black Forest can be relied on. In my view there is no useful comparison to be made with the Sellafield case.

A.35 The March 1995 RWMAC/ACSNI report [GOV/409] considered that it was possible and desirable to go beyond the adoption of simple qualitative geological and hydrogeological criteria; a more quantitative approach should be adopted to assist in discriminating between potential areas and sites. The study group advised that simply setting a performance criterion for a multi-barrier repository system as a whole lacks clarity and transparency about the performance expected of the component barriers, and concluded that public confidence would be greatly increased if performance indicators could be clearly established (separately and jointly) for each of the component barriers before the start of the site selection process. In particular the study group felt that quantitative performance indicators of the geological barrier of potential sites would be helpful. It noted that the approach to site selection to date had been based on qualitative considerations, firstly of rock types and then of potentially suitable hydrogeological environments. It contended that given the large amounts of information available on the geology and hydrogeology of the UK, alternative quantitative approaches to potential site performance would be feasible.

A.36 The report developed the idea of a groundwater return index (GRI) that could be used as a site selection tool. The initial exercise would identify regions with the highest GRI, and only then would disqualifying criteria be applied, such as areas of exceptional landscape, wildlife or amenity value, concentrations of population, old mining, etc. The GRI would be a relative measure of groundwater travel time from a hypothetical repository to the point where the groundwater enters the human environment and takes account of porosity, flow path length, hydraulic conductivity and groundwater head loss.

A.37 The whole concept and usefulness of the GRI was reviewed and severely criticised by BGS in its subsequent report for Nirex [NRX/14/5]. The BGS pointed to various computational difficulties but, more fundamentally, claimed there are serious deficiencies in the availability of the requisite geological and hydrogeological information. In particular it notes that in many parts of the UK there is considerable uncertainty as to the geological formations present at depths typical of those considered for deep disposal of radioactive wastes; that the properties of such formations are poorly known, especially non-aquifer rocks of the types normally considered for radioactive waste isolation; that it can be very misleading to apply values based on 'generic' hydraulic conductivity data obtained from alternative, apparently geologically similar formations; and that very little is known about vertical hydraulic gradients or groundwater salinity/density variations at depth in the UK.

A.38 I consider that the BGS assessment of the RWMAC/ACSNI study group's suggested use of quantitative indicative criteria is broadly justified and is largely a reflection of the reservations BGS has about the scope and usefulness of available relevant geological data, in its own archives or elsewhere. An important conclusion of the May 1995 BGS report - which will effectively represent the current position - was that the sparsity of hydrogeological data for deep geological formations in the UK is such that considerable subjectivity would be involved in determining index values for the vast majority of potential sites and that there is no certainty that contoured maps of GRI would be more objective as tools for site selection than maps showing the distribution of generic hydrogeological environments. I consider that the factors highlighted by BGS also give some indication of the difficulty of making even preliminary safety assessments at the early stages of site selection for localities representative of the main generic hydrogeological environments. I return to this in paras. B.40-46.

Nirex approach to geological criteria

A.39 From the outset and during the site selection procedure up to the time of the MADA exercise, Nirex appears to have fully embraced the validity and usefulness of these qualitative criteria in guiding the selection process. However, with the specialist aid of the British Geological Survey, it translated the guidelines into a document that particularly recognised those factors that I consider to have special significance, namely the prime importance of hydrogeological environments and the importance of lack of geological complexity. The paper by Chapman, McEwen & Beale, 1986 [COR/614], which was published by IAEA, developed what was considered to be a novel concept of hydrogeological environments for deep ILW disposal, departing from earlier guidelines for HLW repository site selection by placing increased emphasis on the regional groundwater regime in the vicinity of the potential host formation, rather than simply considering the properties of the host rock itself. Indeed it stated that it was necessary for the site selection process to be based primarily on defining what are considered to be suitable large scale hydrogeological environments.

A.40 Although stressing that the well understood guidelines still needed to be followed, the new approach was that it is the 'requisite features' of the geological environment that needed to be considered, namely:

- predictable groundwater flow paths, preferably long and resulting in progressive mixing with older, deeper waters or leading to discharge at sea;
- very slow local and regional groundwater movements in an area with low regional hydraulic gradients;
- ease of construction to allow for economic repository design;
- meeting the many accepted caveats regarding seismicity, depth, etc.

These factors were endorsed by Nirex in the PERA document [COR/501].

A.41 On this basis the five generic environments considered to be most suitable for deep disposal of long-lived wastes in the UK were defined, with the aim of producing a shortlist of potential repository sites for thorough investigation and intercomparison. I judge the most significant features of these 5 environments to be:
(a) Inland Basinal Environments - mixed sediments with a high proportion of low

permeability formations; regional groundwater movement would be mainly confined to higher permeability units and would tend to follow the dip of the strata towards the centre of the deep basin. Near stagnant conditions would be expected in the centre of the basin and mixing of waters from one formation to another would only be by diffusion or very slow vertical advection. By locating a repository on the flank of the basin, in one of the low permeability units, groundwater flowpaths would be downward and long, and migration times would be maximised.
(b) Seaward Dipping and Offshore Sediments - this requires a similar mixture of sedimentary strata; groundwater movements would be towards and under the coast and very slow, becoming almost zero at depth in sub-seabed formations.
(c) Low Permeability Basement under Sedimentary Cover (BUSC) - this assumes basement rocks that are hard and of low intrinsic permeability, below more recent sedimentary cover. The thickness, nature and permeability of the cover are not stated but by analogy with the preceding 2 environments it would be appropriate for the cover to be thick, with mixed sediments including a high proportion of lower permeability formations. This would be compatible with the description that groundwater movement will dominantly occur in the cover, with little anticipated connection to the basement rocks. (If the cover sediments were all of higher permeability then the former would still be true but the latter might not.)
(d) Hard Rocks in Low Relief Terrain - the emphasis is on low relief environments which have little driving potential for groundwater movement. The stated preference for a coastal location, with onshore access to an offshore repository, emphasises the point.
(e) Small Islands - the surrounding sea reduces the tendency for groundwater flow but below the seawater/freshwater interface the groundwater should be essentially stagnant. The permeability of the host rock becomes much less significant in such a situation. The massive dilution potential of the sea is also cited as an advantage.

A.42 It is relevant to note the dimensions on the notional diagrams illustrating the five generic geological environments envisaged by Nirex [COR/614, Figs.1a-e]:
(a) Inland Basinal Environments - the diagram shows a basin 2-5km deep, some 20km from the centre to the margin, and with a repository about half way down the flank;
(b) Seaward dipping & offshore sediments - the regional system is shown as about 20km wide by 2km deep, with a repository located about 8km from the nearest surface outcrops or recharge areas of the water-bearing strata;
(c) Low permeability basement under sedimentary cover (BUSC) - the diagram shows a repository at about 1.5km depth in a system with over 1km of sedimentary cover in a region at least 20km wide, so the repository would be 10km or more from the margins of the system;
(d) Hard rocks in low relief terrain - the diagram shows a coastal location with very low relief (less than 100m) in a system 10km wide, but the repository is shown at about 500m depth and 1km offshore;
(e) Small islands - the illustration shows a repository at 1km depth below an island perhaps 2km wide.
Thus, with the exception of those locations where the repository would be directly below the sea, the hydrogeological system is foreseen as being not less than about 20km wide and the nearest zone of recharge perhaps 10km from a potential repository.

A.43 Nirex describes the Sellafield BVG site (either at the location first anticipated in 1989 or in the present PRZ) as being of the BUSC type or a BUSC variant. Cumbria says that no Sellafield BVG site exhibits the geological and hydrogeological 'requisite features' nor matches the BUSC characteristics, nor indeed conforms to Nirex's five preferred generic types. It contends that the BUSC concept originated with a paper by Bredehoeft & Maini

1981 [CCC/4/1] describing a strategy for radioactive waste disposal in crystalline rocks. Nirex disputes this but avers that in any event the Sellafield PRZ does meet the authors' criteria.

A.44 The authors' essential components were a repository in a hard and stable, preferably low permeability, rock mass beneath a blanket of sedimentary rocks whose groundwater flow characteristics are well understood and can be investigated and modelled by conventional, well-understood theory and technology. Preferred features were that the flow system should operate as an active barrier, so that a long migration path and extremely low flow rate to the biosphere can be assured; that the groundwater is non-potable to minimise the possibility of future human intrusion; and that the repository depth is perhaps 1km, where the rock would be relatively unfractured and low in permeability. The emphasis was on low regional topographic differences to minimise differences in hydraulic head and on the advantage of having a layered sedimentary system with relatively higher permeability aquifer layers underlying lower permeability confining layers, to damp out still further even these head differences in the basement at depth.

A.45 These criteria certainly match the BUSC concept but the dimensions of the examples quoted reflect the scale of continental USA and could not be matched in the British Isles: the Maryland example is at a depth of 900m, about 55 km from the surface exposure of the basement strata, and the maximum topography across a region 200 km wide is only 30-60m; the Colorado-Kansas example is about 480km wide with a fall in topography of no more than about 900m, less than 2m per km. It is evident that in BUSC environments there is great advantage in having very subdued surface relief, and relatively thick sedimentary sequences with extensive horizontal uniformity and with significant low permeability layers that restrict vertical flow.

Radiological Criteria

A.46 The fundamental principle of radiological protection is that the risks associated with practices involving the radiation exposure of humans should be kept to acceptable levels, by which I understand the risks to individuals, whether workers or members of the public, should be low and comparing favourably with other risks in normal life. This forms the basis for the ICRP system of dose limitation, incorporated in the IAEA Basic Safety Standards and accepted by many national authorities. Radiological protection in the UK is based on recommendations of the ICRP. The principal current document is the '1990 Recommendations of the International Commission on Radiological Protection' (ICRP 60) [GOV/506]. These recommendations are incorporated in the basic safety standards established under the Euratom Treaty and are binding on EU Member States. The 1995 White Paper [GOV/508, para.56] notes that the Euratom Basic Standards are being revised to takes account of changes in radiological protection criteria recommended by ICRP 60.

A.47 ICRP recommendations distinguish between circumstances where control can be applied to exposure and those where it cannot. These principles are carried forward in HMIP's draft Guidance [HMP/1/1]. During the operational period of a facility, before control is withdrawn, the radiological impact is to be assessed on the basis of source-related and site-related dose constraints. After withdrawal of control, that is to say, the post-operational phase extending into the distant future, radiological protection will be assessed on the basis of risk criteria. It is the latter with which we are principally concerned when considering site selection criteria for deep underground repositories.

A.48 The draft guidelines [HMP/1/1, paras.6.18-6.20] require, in addition to the design target and best practicable means, that it be shown as unlikely for radionuclides from the disposal facility to lead at any time to significant increases in the levels of radioactivity in the accessible environment. This is to restrict the probability of significant local accumulations of such (i.e. artificial) radionuclides. The significance or not of an increase would depend, according to the draft, on more than one factor, notably the comparative radiotoxicity of different radionuclides and ambient variation of levels in local environmental media. Nirex, on the other hand, wishes the emphasis to be on overall levels of radioactivity, which would seem to me to be somewhat counter to the purpose of restricting accumulations of artificial radionuclides. Also, in some places natural radiation levels are of course relatively but consistently high: but I note that the regulators anticipate that this additional requirement would come into play for periods of non-habitation or for the very long term.

Period of control:

A.49 During the period before control is withdrawn, ICRP 60 recommended a dose limit of 1 mSV/y exposure to members of the public but the UK has been operating a target of 0.5 mSv/y in respect of assessed dose arising from radioactive waste discharges from any single nuclear site, and in the White Paper the Government accepts NRPB advice that a maximum constraint value of 0.3 mSv/y should replace this target when determining applications for discharge authorisations from a single new source. A dose constraint of 0.3 mSv/y represents an upper bound on optimisation and implies a maximum level of risk of about 10^{-5}/y.

A.50 The Government proposes also a lower bound for risk optimisation, similar to the area of broadly acceptable risk recognised in the HSE's Tolerability of Risk concept (TOR), namely an annual risk of death not exceeding 10^{-6}. This broadly equates to a lifetime individual dose of 0.03 mSv/y but the Government has decided to set a more cautious threshold value of 0.02 mSv/y. If exposures are calculated to be below this figure, the regulators should not seek further reductions provided they are satisfied the operator is using the best practicable means to limit discharge.

Long term requirements:

A.51 The current basic standard on long term radiological protection of humans and the environment is the IAEA RADWASS Safety Fundamentals document of September 1995 [GOV/504]. The White Paper [GOV/208, para.81] endorses the proposition set out in the Fundamentals Document that radioactive waste should be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today. This was more recently confirmed by the Collective Opinion of the NEA Radioactive Waste Management Committee on 'The Environmental and Ethical Basis of the Geological Disposal of Long-lived Radioactive Waste', 1995 [FOE/1/4]. This added that geological disposal should ensure that residual radioactive substances reaching the biosphere will be at concentrations that are insignificant compared, for example, with the natural background levels of radioactivity [ibid., p.16]. A similar regard to limit the radiological detriment to any individual in the future has applied since at least 1983 [GOV/502, s.4.2.3.3].

A.52 The NRPB has suggested that site-specific risk calculations may be made with some confidence up to 10,000 years and thereafter hypothetical reference models of critical groups and the biosphere should be used to calculate the risks, although a risk constraint should still apply up to about 1 million years. Beyond that time qualitative arguments should be used to show that the likelihood of any sudden, significant increases in risk is low [GOV/208, para.80 & GOV/409, para.3.31]. The recent RWMAC/ACSNI report [GOV/409, para.3.42] expresses the view that for times beyond about 10,000 years after repository closure, the uncertainty in the possible biosphere conditions and in human behaviour is too great for estimates of risk to be meaningful.

A.53 The White Paper [para.78] defines the quantitative objective for repository design as an individual risk target of 10^{-6}/y of developing either a fatal cancer or a serious hereditary defect (in contrast to the 10^{-6} risk of death set as the optimisation lower bound for discharges). HMIP's draft guidelines [HMP/1/1, para.8.21] additionally require a developer to support his safety case with indicators of collective radiological impact as a measure of how widespread any significant elevation of risk may be as a result of radioactivity from the disposal facility. RWMAC has said that collective dose is a useful comparative measure of the global scale of a radiation source [GOV/411 para.2.20(ii) & GOV/406 p.51]. Nirex has reservations that attempts to calculate doses to large numbers of people over very long periods of time can be misleading. It considers that collective dose estimates based on declared population and behaviour assumptions over limited timeframes may be a useful comparative indicator of design options, but will only be supportive to the main arguments advanced in the safety case. I am in general agreement that estimates over a period of up to say 100,000 years after repository closure may be useful but thereafter the validity of such calculations becomes questionable. HMIP's consultation draft [HMP/1/1, para.6.14] agrees that at times longer than those for which conditions can be modelled, scoping calculations or qualitative arguments may be used.

<u>Optimisation of Radiological Risk</u>:

A.54 Nirex maintains there is no requirement to select a site providing a level of risk even lower than what it considers to be its 10^{-6} repository design. There appears to be no basic requirement in international guidelines or national regulations or guidelines for the principle of radiological risk optimisation to be applied at the site selection stage when more than one site is under consideration and being compared. It is, for example, a general requirement of the 1983 IAEA radiological protection guidelines relating to underground radioactive waste disposal [GOV/502, para.4.2.1 & Annex I] that 'All radiation exposures, during both operational and post-operational periods, shall be kept as low as reasonably achievable, (ALARA), economic and social factors being taken into account'. However it is clear that in this context the ALARA principle applies only to the specific site put forward for approval or actually in operation, and is not directly applicable to the site selection process. (This may be compared with a 'Basic Requirement' elsewhere in the same document [ibid., para.4.3] that '<u>Siting</u>, design, construction, operation and post-operation of the repository shall be optimised to ensure that adverse effects on the environment and natural resources now and in the future are kept as low as reasonably achievable'. Thus optimisation of siting is required under the heading of Environmental and natural resources protection but not under that of Radiological protection.)

A.55 The 1984 Green Book [GOV/302, s.5.4] stated that the authorising Departments would "require to be satisfied that in selecting his preferred site, the developer has not ignored a clearly better option for limiting radiological risks". Although the document explained that a developer "will not be expected to show that his proposal represents the best choice from all conceivably possible sites" and envisaged that factors other than radiological ones may influence the choice of site, I would say that it arguably required Nirex to give preference to radiologically better shortlisted sites. However the Green Book is now specifically superseded by the recent White paper in terms of policy.

A.56 The HMIP draft guidelines [HMP/1/1, para.6.9] require that if the estimated risk of a fatal cancer or a serious hereditary defect is above the annual 10^{-6} target, the Inspectorates will need to be satisfied that an 'appropriate' level of safety is assured but do not define what might be 'appropriate'. No specific upper bound is proposed and the document is silent as to whether the Tolerability of Risk (TOR) principle would be applicable. In contrast the 1984 Green Book [GOV/302, para.3.8] expressly reduced the target dose from one equivalent to a risk of 10^{-5} to one of about 10^{-6} to allow for uncertainties in exposure pathways and health effects and possible new exposure sources. Similarly the RWMAC/ACSNI group [GOV/409, para.4.35] recommended that an allowance should be made for geological uncertainty. It recommended that site selection should identify perhaps 10 to 12 areas "with inherent characteristics likely to be favourable and each expected to meet the overall safety criteria more than adequately..".

A.57 The parties opposing Nirex on the basis that background radiation should be a criterion of repository site selection seem to be troubled mainly by uncertainties concerning the additive, promotional and cumulative effects of artificial radionuclides in the environment. The draft regulatory guidelines do address the probability of accumulations of such radionuclides in the environment (see para.A.48 above). This is not essentially a geological or hydrogeological issue but I would comment that there does seem to be some tendency to overlook the positive function of the Sievert as a qualitative measure of the harmfulness of ionising radiation [see eg GOV/306, para.14].

Comparison with Background Radiation

A.58 Radon and its progeny amount typically to the source of roughly half the average radiation dose of a current inhabitant of the UK [GOV/416, s.2.4 & tables 2 & 35]. Radon gas derives from the radioactive decay mainly of uranium but also of thorium, which occur naturally in UK soils and rocks. The areas primarily affected are parts of Cornwall, Devon, Somerset, Northamptonshire and Derbyshire [ibid., figs.7 & 8]. Positive protection measures in the UK relate to 'Action Levels' and 'Affected Areas'. An Affected Area has 1% or more of present or future homes potentially above the Action Level of $200Bq/m^3$. Cumbria as a whole is shown in the category having 0.3-1% of such homes above the Action Level [ibid., fig.2], below the threshold for Affected Area status. I am not aware of any sub-division of the County in respect of radon affected houses, unfavourable to West Cumbria or otherwise.

A.59 A 1995 NRPB study for the French Institut de Protection et de Sûreté Nucléaire suggests there is no lower threshold for health risk from radiation exposure [GNP/1/3]. The report was a detailed review of data available for assessing the risk of radiation-induced cancer with particular emphasis on assessing risks at low doses and low dose rates. It concluded that its studies of low-LET [linear energy transfer] exposure are consistent with a linear trend in cancer risks at low doses without threshold although it did recognise that there is a practical limit to the lowest doses at which excess risks have been detected in epidemiological studies.

A.60 It follows therefore that any ultimate escape of radionuclides from a repository into a populated biosphere, no matter how slight, will result in some deaths and serious health effects. However the principal criterion for repository design - the 10^{-6} risk target equating roughly to an individual receiving a dose of 0.03 mSv/y for a lifetime - is set well below the risk implied by exposure to natural background radiation in the UK, which varies from about

1 in 10,000 per year to more than 1 in 1,000 per year [HMP/1/1, para.6.20]. Even an exposure of 0.3 mSv/y and health risk of 10^{-5}, equating to the upper end of the Tolerability of Risk zone that might be applied by the regulators, falls well below typical natural exposures and risks.

Conclusions on basic criteria for repository

A.61 Although international and national guidelines emphasise that in judging a specific repository it is the total system that must be taken into consideration and the geological environment should not be considered in isolation, I consider that during the site selection stage in reducing the target areas to a small number, priority should be given to those qualitative geological and hydrogeological factors that are most likely to lead to a robust and demonstrable safety case: a preference for regions of low hydraulic gradients; a preference for uniform rock formations in comparatively simple geological settings with few major structural features or potential transport pathways since such environments are likely to be more readily characterisable and predictable; and a preference for regions that are relatively stable in terms of earth movements and other long term geodynamic effects.

A.62 Insofar as I understand the radiological arguments, I do not consider that the levels of background radiation from natural or artificial sources should normally have much influence in the selection of a potential repository site compared with the radiological protection properties of the host geological and hydrogeological environment.

B SITE SELECTION CRITERIA

Appropriate site selection methodology

B.1 A favourable geological environment is crucial to the selection of an appropriate, safe, underground disposal site for the types of radioactive wastes with which we are concerned, firstly because it is expected to act as the principal barrier in confining the radioactivity (and indeed any other harmful substances or effects) and secondly it should have satisfactory geotechnical characteristics for implementing the necessary engineering works. A methodical approach to site selection is therefore most likely to result in the successful identification of suitable sites and the ultimate choice of a preferred location fitting closely the relevant physical and safety criteria.

B.2 Nirex says it has followed the site selection methodology recommended by the IAEA in its 1983 guidelines [GOV/501]. This recognises a number of typical stages: a preparatory stage of planning and general studies; a stage of regional evaluation, to select potential repository regions; then a site identification stage, homing in on specific potential sites; finally site confirmation, to confirm the acceptability of one or more identified sites.

B.3 The comparable IAEA guidelines for HLW/∀-waste disposal [GOV/507, 1994] suggest that suitable disposal sites may be identified either by systematically narrowing in from large regions to specific sites, or alternatively by objectively evaluating one or more designated potential sites identified at the outset as worthy of special consideration. (Examples given of the latter category were existing nuclear sites or land adjoining existing nuclear facilities, because of the potential benefits of such co-location, particularly in relation to reducing waste transportation requirements.) However it seems to me that the latter approach is unlikely to be productive in the UK because of the great variations in its geology and topography over such a relatively compact landmass and the number of geological factors that need to be considered in detail before any potential site could conceivably be designated.

B.4 The preparatory stage of planning and general studies is envisaged as including repository performance requirements, the establishment of area and site selection guidelines, the identification of potential host rock types, and repository conceptual design.

B.5 The objective of the regional evaluation stage described by IAEA 1983 [GOV/501] is to select areas with favourable characteristics for a repository and reduce them to a few preferred areas for further study, done largely by desk and remote sensing studies, supported by some laboratory work and reconnaissance geological and hydrological fieldwork. Additional activities during this regional stage might include selection of potential host rock types and appropriate conceptual repository designs for each; preliminary safety analyses for different systems of natural and engineered barriers; the establishment of factors for preliminary site selection; and site investigation to obtain regional geological properties important for site selection.

B.6 Having narrowed the search to promising areas the IAEA's Site identification stage aims to identify specific potential repository sites. Particular host rocks would be selected for investigation; preliminary sites would be 'characterised' (which presumably would require some physical investigation to obtain site-specific data); preliminary repository designs would be developed, and preliminary safety analyses carried out for specific systems of natural and engineered barriers.

B.7 The 1994 IAEA guidelines on the siting process for HLW/∀-bearing wastes [GOV/507] combine the Regional Evaluation and Site Identification stages into a single Area Survey stage but still distinguish a Regional Mapping phase, starting with large regions containing land having favourable geological, hydrogeological and geographical features then focussing on successively smaller and increasingly more suitable areas, followed by a Potential Site Screening phase in which possible sites are identified within the selected suitable small areas and then reduced to one or several potential sites for further study.

B.8 It is the Site Confirmation Stage that is expected to culminate in the selection of one, but possibly more, favourable sites and lead to specific repository design, construction and commissioning. The acceptability of the identified sites would be confirmed on the basis of criteria established during the previous stage.

Site selection up to the MADA exercise

Definition of original areas of search

B.9 The starting point for Nirex was the work of Chapman, McEwen & Beale, 1986 [COR/614] who took the basic international criteria and translated them into a generic concept for use in NW Europe and specifically in the UK. They defined what they considered to be the five most generically suitable geological environments for deep disposal of long-lived ILWs (the essential characteristics of which were described in A.41 above):
(a) inland basinal environments
(b) seaward dipping and offshore sediments
(c) low permeability basement under sedimentary cover (BUSC)
(d) hard rocks in low relief terrain
(e) small islands.

B.10 On the basis of desk study they identified 'quite precisely' all the broad regions and sub-regions of England, Scotland and Wales conforming to these geological environments.

B.11 For Types (a) and (b) - inland basins and seaward dipping/offshore sediments - they identified the Kimmeridge Clay, Oxford Clay, Lias clays, Mercia Mudstones, and general Permian strata as potentially favourable, being mainly clay-based or evaporitic, at depths between 200 and 1000 metres and of certain minimum thicknesses, and limited by the presence of major fault zones and zones of structural complexity. Much of southern and eastern England was considered to have potentially suitable environments, especially the 'Eastern England Shelf' where the geological complexity is minimised by the absence of significant folding and faulting. The basins between Devon and Dover and the Worcester Basin were considered to be structurally rather complex and the Cleveland Basin to be affected by numerous large faults. Thick Mercia Mudstones are particularly well developed in the Cheshire Basin and there are sedimentary sequences along the West Lancashire and Lake District coast that thicken rapidly offshore into the Irish Sea Basin. It was noted that most of these areas are licensed for oil and gas exploration and production; and that the Eastern England Shelf, the Cleveland, Worcester and Cheshire basins, and parts of the Wessex Basin are considered to be potential geothermal fields.
B.12 As for Type (c) BUSC environments, Precambrian and Palaeozoic basement rocks are present at relatively shallow depth below much of central and eastern England, with a cover of Mesozoic (Permian and newer) sedimentary rocks. Potentially suitable formations are

present over large areas and include Tremadoc shales, siltstones and sandstones, and a variety of Cambrian and Pre-Cambrian rock types, mainly metamorphosed tuffs and sandstones. Areas overlain by Carboniferous limestones and coarse Devonian sediments, relatively limited in extent, were recommended to be avoided and doubts expressed over some igneous intrusive rocks. All areas of basement shallower than 800m below OD were considered. Areas overlain by Carboniferous Coal Measures were excluded as were some adjacent areas of the south Midlands where gas in the basement rocks is thought to have a Coal Measures source. The authors also excluded extensive eastern areas where the cover rocks included the Lower Greensand or Chalk, two major aquifers, and areas to the west having a cover of Sherwood Sandstones, also major water-bearing strata, but a later reassessment by Nirex and BGS led to the reinstatement of the Greensand and Chalk areas. [compare COR/614 fig.9 with COR/501 fig.6.2]

B.13 Relatively limited areas of potentially suitable hard rocks in low-relief terrain, Type (d), were identified, mainly in coastal areas of northeastern Scotland and parts of the Outer Hebrides. A wide variety of rock types were considered including Lewisian (Precambrian) gneiss in Northern Lewis, granites intruded into Moine metasediments in Caithness and Sutherland, granites and Dalradian metasediments in coastal areas north of Aberdeen, and the Caithness Flags (Devonian) of Caithness and around the Dornoch Firth. Also identified were Precambrian igneous intrusive and metamorphic rocks of Anglesey and the Lleyn Peninsula in Wales. It was considered that smaller sub-areas of interest would need to be defined using major faults and discontinuities as boundaries.

B.14 87 potentially suitable small islands larger than 0.5 km^2, without extreme topography, and sufficiently far from the mainland to be hydrogeologically independent were identified, the majority off the west coast of Scotland, or in the Orkneys and Shetlands, with just a few around the coasts of England and Wales.

B.15 It seems to me that the principles followed by Chapman and others up to this point in defining geologically suitable environments and the criteria used to define depths, boundaries and other limits for host rocks were sound. The geographical areas that emerged appear to have been as comprehensive and soundly based as the available geological data would permit. Nirex then amended these areas of search before the process of specific site identification and elimination.

Reduced Areas of Search

B.16 The first step was to restrict consideration to the environments of 'hard rocks in low relief terrain', 'seaward-dipping sediments' and 'small islands' because of the greater understanding of the properties of the geological formations and assurance with which the groundwater regimes could be characterised, but a re-evaluation of the 'basement under sedimentary cover', BUSC, environment soon lead to its re-inclusion. This meant that inland basin environments were given low preference, and indeed I would expect these to be frequently associated with coalfields, salt or evaporite fields and onshore oil and gas fields.

B.17 The PERA document [COR/501, Fig 6.4] shows that two filtering operations were then applied, one on the basis of population density and the other considering landscape and nature conservation.

B.18 Comparison of COR/501 Figures 6.2 and 6.3 shows how the initially identified potential regions and areas of generically suitable type were reduced in extent, without distinguishing between the results of the different tests of population density, landscape and nature conservation considerations, or low preference to inland basins, or any other criteria. However this stage of reducing the broad areas of search eliminated about two-thirds of all potentially suitable sedimentary environments, including Cleveland, the Cheshire Basin, extensive areas of the South Midlands, the southern counties and the northern parts of East Anglia. The BUSC areas also show considerable reductions but predominantly in the heavily populated areas of the home counties. Changes in the areas of low relief/hard rock were described as being due principally to geological reappraisals. The elimination of such a high proportion of all potentially suitable sedimentary formations at this stage is striking, and especially the complete exclusion of inland basins even allowing for their low preference.

The selection and elimination of sites

B.19 From the reduced, but still very extensive, areas of search, the exercise led to the identification of sites - nearly 500 of them - with a potential for repository location. The original identifications were made with the advice of the BGS and planning consultants and taking ownership factors into account. Some sites outside the areas of search were added if they seemed to have potentially favourable features such as both extent and isolation: but of course they also had to have a 'satisfactory' geology, and it is not surprising that none went through to the final stages of selection.

B.20 I note that in limiting the areas of search offshore (for an under-sea-bed repository with offshore access), practical constraints of water depth and avoidance of areas licensed for hydrocarbon exploration were applied. Those seem to me to be reasonable criteria to apply.

B.21 The major reduction in the list of potential sites took place at the very next step, when nearly 500 were reduced to about 200 site showing 'real potential'. This was done on the basis of (a) a preliminary evaluation of their specific geological setting and (b) further environmental impact and planning factors. Geology therefore had some influence but it was not the sole criterion.

B.22 A reduction then from about 200 to about 160 sites was made on the basis of a closer review of site ownership. The following step, from about 160 to 120 sites, was on the basis of size of available parcels of land, with defined target sizes for inland and coastal sites but said to be applied flexibly where other attributes were favourable or there was a reasonable prospect of assembling sufficient land in a locality. Hence these two steps of reduction, from 200 to 120 sites, were predominantly non-geological.

B.23 The next critical step was the reduction from about 120 to 39 sites. This was on the basis of their geological potential to host a deep repository: the available data for all 120 remaining sites were re-examined in further detail by BGS. A geological profile of each site was prepared, so that likely hydrogeological characteristics could be assessed: and the selected candidates were those likely to perform best in hydrogeological terms.

B.24 I view this step, from 120 to 39, as having been a very important stage since the assessment and selection was made entirely on grounds of geological suitability of the locality and host environment, and its intention was to select not merely adequate sites but the best in terms of performance of the geosphere system. It was after this stage that, according to Nirex's correction of PERA, the Sellafield B site (Site 10) was added.

B.25 The reduction from 39 sites to 19 - two offshore and 17 land-based - was made on the basis of likely site availability and a progressive evaluation of 'specific sites' taking account of a detailed appraisal of radiological safety, geology, socio-economic and environmental issues, repository design concepts and transport. Thus some additional account was taken of geology at this stage but the post closure radiological safety assessments were still being made on a generic basis.

B.26 The final step prior to the MADA exercise was the reduction from 19 to 12 sites. All factors are said to have been reviewed: socio-economic, land-use planning and environmental, preliminary costs and designs, and geological. The BGS considered uncertainties associated with the geological data and how better data could be obtained by ground investigations.

B.27 In nominating the selected 12 there was a conscious intent to keep options open by including sites from each of the four rock environments and from offshore hard rock and sedimentary rock locations. Because of the difficulty of comparing and ranking locations from different geological categories and to minimise the risk of a promising location being discarded, sites additional to the leading candidate in each land-based category were included for further consideration. Thus the final 12 were: Sellafield B; BUSC, 3 sites; inland hard rock, 1; and coastal hard rock/low relief (Dounreay), 1; islands, 2; seaward dipping sediments, 2; offshore, 2 sites (sub-divided for some purposes into 3, and unspecified as to whether sedimentary or hard rock type).

The late introduction of Sellafield B (Site 10)

B.28 Sellafield A (Site 9) was one of the two seaward dipping sites in the final 12. The repository would have been in anhydrite deposits within the thick sediments. This was originally conceived as offshore but accessed from land, but by the time of the MADA exercise the repository would have been directly below the Sellafield Works. It is somewhat surprising that Sellafield A reached this stage of shortlisting having regard to the fact that the anhydrite host rock has a history of being mined nearby and the general presumption against choosing sites with exploitable minerals in order to minimise risk of future intrusion.

B.29 However at an early stage in the sensitivity analysis of the shortlisted 12 it emerged that seaward dipping sediments performed consistently less well than other environments when all attributes were taken into account (BUSC concepts having been identified as giving the best overall post-closure radiological safety for land-based repositories).

B.30 Sellafield B had clearly been treated in a different manner to the initial 500 sites and had not been through the same steps of geological selection, review and sieving. There had been a primary consideration of geological environment in compiling the initial pool of nearly 500 and a further consideration of geology in reducing the list to about 200. The major reduction from 120 to 39 sites was made solely on the basis of geological suitability and the identification of sites likely to perform best. A site inland of Sellafield in the BVG basement is not claimed to have gone through that step. However at each subsequent reduction, a review of geological factors was made in parallel with assessment of the numerous non-geological criteria.

B.31 In the Nirex and BGS studies to define areas of search, the coastal zone of west Cumbria was identified as 'seaward dipping sediments' but no BUSC areas were mapped in the district. Nirex nevertheless now insists that Sellafield B can properly be called a BUSC site because it has what it says are the two essential elements: low permeability of the basement rock, and groundwater movement dominantly in the overlying sedimentary cover. However the generic environments were defined on the basis of requisite features that included very slow local and regional groundwater movements in an area of low regional hydraulic gradients, and predictable groundwater flow paths, preferably long and resulting in progressive mixing with older, deeper waters or leading to discharge at sea.

B.32 On the contrary, the topography and geological situation of the Sellafield area do not suggest low regional hydraulic gradients nor long flow paths. From the groundwater recharge area of BVG at outcrop just inland of Longlands Farm, Sellafield to the discharge zone at the sea's edge the distance is barely 6 or 7km and the fall in elevation is over 125-150 metres. Moreover the Sellafield concept envisages the primary mixing of groundwater with newer, shallower water in the sedimentary cover rather than progressively with older, deeper waters or the sea, albeit there that could well be an ultimate discharge to the sea. Furthermore, and also contrary to the preferred features described by Bredehoeft & Maini [see A.43 & .44 above], the groundwater at Sellafield is potable and the local SSG is classified as a major aquifer by the NRA.

B.33 There are a number of other features about the geological setting of the Sellafield district that make the late inclusion of the Sellafield Basement site seem surprising:
(a) The Sellafield district, regardless of the precise site, lies along the boundary between major geological structural provinces, the Irish Sea Basin and the Lake District Dome, where a degree of structural complexity might be expected, even if it was not thought to be a tectonically active zone.

(b) The basement rocks in which a repository would be constructed - the Borrowdale Volcanic Group - are a thick sequence whose hydrogeological characteristics were almost unknown but whose lithological variations and stratigraphical relationships are well exposed at outcrop and relatively well understood though known to be complex and open to alternative interpretations. In choosing the BVG, an eruptive volcanic sequence, there could have been no reasonable expectation of vertical and lateral consistency of lithology over any great distances, even neglecting considerations of faulting, and this could be expected to make the geology relatively difficult to characterise and might make the hydrogeological regime more variable and difficult to investigate.

(c) The Sellafield Basement site considered in PERA and Site 10 of the MADA exercise was in the Pelham House School Estate, which Nirex knew to be in an area where Carboniferous limestones were present above the basement rocks and below the Triassic sandstones. [COR/501 Fig.8.2 & Table 8.1] This is somewhat surprising because it might reasonably have been suspected that the limestones contained 'karstic' solution features such as eroded joints and bedding planes or even cavities, either associated with the period of haematite mineralisation in the district or with changed groundwater flows in more recent glacial and periglacial times. Indeed Chapman & others, in defining the BUSC areas of the UK [COR/614], had recommended that areas where Carboniferous limestones were present should be avoided. (In that case they were thinking of parts of the south Midlands.)

B.34 Thus the Sellafield Basement site introduced at a late stage did not comfortably meet what were earlier seen as requisite features. Nor did it comfortably fit into one of the previously adopted generic types of target geology. Nirex introduced a site that might reasonably have been expected to be difficult to investigate and characterise. If the Sellafield B site had been included in the original pool of nearly 500 potential repository locations and had passed through the same qualitative geological sieving process as the others then I would have expected it to have been excluded on comparative geological and hydrogeological grounds at a relatively early stage.

B.35 The preliminary post closure radiological performance assessment for a repository located near the Seascale Fault Zone, as assumed in Nirex 95, was not as good as Nirex expects now that the preferred location has been moved towards the NE corner of the PRZ. This suggests that for Sellafield the safety case is sensitive to the precise location of the DWR within a limited area of PRZ. This might not have been the case if a site had been selected that more obviously conformed to one of the five preferred generic types since the geology and hydrogeology would be expected to have sufficient lateral consistency that the exact plan position of the repository should not be so significant.

<u>Overall site selection down to the MADA exercise</u>

B.36 IAEA guidelines envisage ideally a stepwise process of screening starting with regions of interest, then selecting and focussing in on suitable small areas, followed by the identification of potential sites within those areas. Although claiming to have broadly followed this process, Nirex is now also emphasising the reference in the guidelines to the need to take local conditions into account, and to the dependency of the host rock's suitability on individual circumstances.

B.37 Chapman & others [COR/614], having defined the original broad generic areas of search, considered that the next step must be more detailed desk appraisals to define sub-areas with greater potential, but thought that for many areas this would require the acquisition or re-analysis of detailed seismic and deep borehole data. Only in simpler areas did they consider it feasible to begin assessing specific sub-areas or even specific sites nominated on non-geological grounds, and expressly stated that the east coastal and contiguous inland area of England defined by the Eastern England Shelf to the Cleveland Basin, appears to be one of the least complex, most predictable regions in which to target the initial search for specific sites for more detailed assessment.

B.38 The decision to include the leading candidate and at least one other in each category because of the difficulty of comparing sites from different geological environments indicates that the importance of geology in the performance of a site was recognised, yet the selection and sieving process which arrived at that point does not appear to have systematically identified the geologically and hydrogeologically most promising and favourable general locations before applying non-geological factors. On the other hand the process might have been expected to eliminate Sellafield B, for the reasons given in paras. B.33-34.

B.39 The selection process started with 500 sites, all in generic environments considered likely to give high radiological safety because of their gross geological characteristics, and four out of five of those generic types were checked with a preliminary PCRA. At the important 120 to 39 sieving stage those sites likely to perform best hydrogeologically were identified and retained, so the 39 should have been among the remaining ones most likely to be able to meet a 10^{-6} risk target. Although non-geological criteria may have removed potentially safer sites from the initial list of nearly 500, it would have been a poor selection process that, by the time the numbers had reduced to 39 or fewer, had not produced sites that not only met broad land use considerations but were also very likely to meet 10^{-6} or near.

The MADA Exercise

Quality of geological profiles available to the MADA team

B.40 It is appropriate that the British Geological Survey should have been closely involved with the process of site selection since BGS, as our national mapping agency, holds an enormous body of geological information and expertise accumulated over more than a century and a half. This includes primary geological mapping data and compiled maps not only of the land surface but also of the UK continental shelf; details of the large numbers of boreholes, shafts and wells together with reference collections of rock core and many other geological specimens; national and regional geophysical and hydrogeological mapping; records of mineral workings and mineral resources; plus the results of a large body of applied geological research from micropalaeontology to engineering geology. A proportion of the records are held on a 'commercial in confidence' basis, especially those associated with more modern mineral and energy resource explorations, but even so it is often possible to make use of abstracted key data.

B.41 Yet despite this great mass of data there is relatively sporadic information on the deep geology of the UK mainland and coastal margins at the depths and in the general territories that may be appropriate for siting a deep underground repository for ILW. Areas of mineral potential, especially coal and oil have been explored to great depths by direct investigations and geophysical methods; other minerals (metallic and evaporites) and major aquifers explored to intermediate depths. It therefore follows that areas meeting the criterion of unlikelihood of human intervention (i.e. no mineral resources nor aquifers) are likely to be least explored and characterised.

B.42 A paper describing the role of fossil evidence in understanding the broad (early Palaeozoic) basement geology of eastern England [NRX/14/4] reviews the available deep borehole data over a very wide area within that region. It gives a good indication of how relatively few physical investigations have reached the buried older rocks and how limited the investigations have been in them. The paper identifies and gives some details of approximately 70 boreholes in the large block of country from Lincolnshire to the South Midlands to North Kent, and taking in East Anglia. It notes that a further about 30 boreholes in an area of approximately 600 sq.km between Warwick and Rugby also encountered early Palaeozoic rocks beneath more recent sedimentary cover. Many of these holes penetrated just a few metres into the basement and fewer than 10 appear to have penetrated more than 100m into the older strata. In most cases though it has been possible to identify that part of the geological succession to which the basement rocks belong, the palaeo-environment in which they were formed, and a general indication of the inclination of the strata and effects such as weathering and cleavage. This gives some indication of the broad geological structure and history of the region but little indication of local variability.

B.43 A similar relatively sparse and uneven distribution of deep holes would be expected elsewhere in Britain, including the Sellafield district where, up to the start of Nirex drilling in 1989, most previous boreholes known to have penetrated the sedimentary cover had not been drilled far enough into the Borrowdale volcanics to be very useful. The British Geological Survey has acknowledged the following shortcomings in the available data relevant to deep waste repositories [NRX/14/5]:

- in many parts of the UK there is considerable uncertainty as to the geological formations present at depths typical of those considered for deep disposal of radioactive wastes (say 200-1000 m below ground)
- the availability of reliable hydrogeological data for deep formations in the UK is extremely patchy. Reliance has to be placed on estimates but there are large uncertainties associated with inferred values based on sparse data
- much hydrogeological information (including estimates of hydraulic conductivity) exists for the main UK aquifers but the properties of non-aquifer rocks (including all the rock types normally considered for radioactive waste isolation) are by comparison much more poorly known.
- very little is known about vertical hydraulic gradients in the UK at the relevant depths, likewise for groundwater salinity and density variations except perhaps in some inland sedimentary basins.
I would say that regional hydrogeological conditions and groundwater heads are least well mapped and understood in zones of significant topographic relief such as the margins of the Lake District.

B.44 The primary geological information available to the MADA team on the final dozen sites was essentially the same as available from the outset, except that the level of geological and hydrogeological interpretation had increased.

B.45 In addition to knowledge of the basic geology and groundwater regime of a locality, the 1983 IAEA guidelines recommended that at an early stage in the siting process a preliminary assessment is made of the predictability and effects over appropriate time periods of future geodynamic phenomena, including tectonics, seismicity, volcanism and climate changes. The search should be directed at finding geological host environments and geographical settings where geodynamic processes or events are unlikely to impair the isolation capability of the overall disposal system and lead to unacceptable radionuclide release. Nirex and BGS will have had available to them good evidence on a broad (global and regional) scale concerning such matters but less good at the more local level needed to discriminate between sites.

B.46 Thus there would have been an uneven quality of data in the geological profiles available to the MADA team when they came to consider the final 12 sites. Supporting material such as geophysical, hydrogeological, geochemical and hydrochemical data, and basic physical properties of the rocks could have been quite widely variable from site to site.

<u>Geological aspects of the MADA exercise</u>

B.47 The MADA Group constructed a hierarchy of attributes that they considered relevant to the comparison of sites. 30 attributes were chosen, grouped under the major nodes of costs, robustness, safety and environment. [NRX/18/6 table 1 & fig.1] Geological and hydrogeological aspects of repository siting and performance were reflected to a greater or lesser extent in one-third of all the attributes but explicitly in only 2 out of the 30.

B.48 Under the Robustness node, Repository subdivision, are two measures of 'geological certainty': <u>Attribute 12</u> - geological predictability (also called geological certainty), and described as a measure of known lack of discontinuities and of possible but as yet unknown features; and <u>Attribute 13</u> - repository investigability, described as the likelihood that investigations will provide good data, and a measure of the required scale of investigations and availability of techniques to carry it out. In the base case, these attributes are given a weighting of 3.27 and 0.82, a total of 4.09 out of 100 [NRX/18/6 table 4].

B.49 For both attributes, sites were scored against a rating model: different features of the sites gained points that were weighted and summed to give an overall rating on an interval scale, then converted linearly to preference scores. The preference scores would ordinarily go from zero (least preferred) to 100 (most preferred). In the case of Investigability (Attribute 13), Sites 11 & 12 (Offshore West Shallow and Deep) scored Zero and minus 22 respectively, and Site 13 (Offshore East) also scored poorly. To have achieved such poor scores Offshore West must be almost uninvestigable, but if a repository site is not capable practically of being geologically investigated from the surface it would appear impossible to make out a safety case for it, or to establish even the principles of engineering design, or to monitor baseline conditions and the effects on the geosphere of repository construction and operation. It is therefore hard to see how such a site came through to the final dozen.

B.50 As for geological Predictability (Attribute 12), Site 9 (Sellafield A in anhydrites 1300m below Sellafield Works) was judged to be the least good, with a score of Zero, and Site 10 (Sellafield B in the volcanic basement rocks) the second worst, with a score of 34. All other sites had a rating of 63 or above. The low scores at Sellafield do not necessarily mean that those sites were considered to be seriously unpredictable, but that relative to the other sites in the MADA pool they were recognised as being distinctly less good in that regard. On the other hand I find the poor ratings unsurprising in the light of my conclusions in paras. B.28-35 above.

B.51 Three other geologically related attributes appear under the Robustness of repository nodes: Attribute 8 - known engineering, appears to reflect past geotechnical, mining and construction engineering experience in similar strata at similar depths and in similar geological circumstances, and had a weighting of 4.08 (the highest weight after the 4 attributes of repository and transport operating and capital costs);
Attribute 9 - flexibility, is described [NRX/18/6 table 1] as the potential to accommodate design variations, explained in evidence as primarily representing the ability or otherwise to site a repository at varying depths. This was given a base case weight of 1.63;
Attribute 11 - invulnerability, is described as the potential for losing the repository as a result of catastrophic events, which would include natural events such as meteorite strike and severe earthquake, but also human actions such as bombing, sabotage and air crashes. It was also given a weight of 1.63.
Together these 3 attributes carried a base-case weighting of 7.34 and, added to the figure for the two 'geological certainty' attributes, give a total weight of 11.43 for these predominantly geological factors, or over 95% of the weight given to Repository robustness.

B.52 Each of the Offshore sites (sites 11-13) rated poorly on a preference scale under Attribute 8, Known Engineering, presumably in the main because of anticipated difficulties and lack of experience of shaft sinking from offshore structures [COR/501 s4.3], and the Offshore West concepts (sites 11 & 12) rated badly in terms of Attribute 11, Invulnerability, presumably because of the risk of damage to gravity platforms founded on the seabed.

B.53 Attribute 9, Flexibility, was assessed against a rating model. Sellafield A (site 9) scored Zero. Site 5, the other seaward dipping sediments environment, also scored badly as did Site 13, Offshore East, in each case presumably because of local geography. What is surprising is that the remaining sites all scored 100, implying that they were all equally unconstrained by the thickness and depth of the host rocks, their vertical and horizontal variations in lithology and geotechnical characteristics, the absence of major faults and the like, despite the differing conceptual repository designs and widely varying numbers and dimensions of vaults and means of access appropriate to the various preferred geological environments [COR/501 chap.4]. No discrimination was made on the basis of this attribute between the 10 sites that were each given a score of 100.

B.54 Attribute 27, Economic Resource Sterilisation under the node of 'Impacts - Environment', is a measure of the number and value of resources forgone. Values were assigned against a simple rating scale but the attribute was given a base case weighting of only 0.26. Economic resources might include deeper minerals and groundwater as well as surface potential such as forestry and fisheries, but in general I would have expected significant aquifers or areas with deeper mineral resources to have been weeded out during the site sieving process (to minimise risk of human intrusion or radiological contamination of groundwater).

B.55 The four Post Closure Safety attributes, regarded by many objectors as the attributes that ought to carry the greatest weight in the MADA exercise, each have a significant geological basis. Attributes 18-20 represent radiological risk to future populations: safety of most exposed individuals; collective risk to society over the short term (10^5 years); risk to society over the long term (10^5 to 10^8 years). Attribute 21 is post closure repository integrity.

B.56 Attribute 21, Post-closure integrity, is the chance that the facility will be disturbed by human intrusion. Risk assessment calculations have put the probability for the various sites in the range 10^{-6} to 10^{-9} but the risks appear to be polarised towards one end of the range or the other. (Two had preference scores of zero, Sellafield A had 80, and the rest 100.) Since the greatest post-closure risk of intrusion into a deep under-land repository appears to be associated with drilling explorations and mining operations there would appear to be some duplication between this attribute and Attribute 27, Economic Resource Sterilisation.

B.57 Attribute 21 was given the relatively high weighting of 3.18 although it has little discriminating power except perhaps to help eliminate Sites 13 and 5. The combined weight of all three Post-closure Radiological Safety attributes (18-20) was only slightly more, at 3.59 (with values of 3.18, 0.03 & 0.38 respectively).

B.58 Attributes 18 to 20 represent the calculated performance of an engineered repository system as a whole and as such encapsulate all the assumptions made about the composition and behaviour of the waste, the engineered barrier, the geological and hydrogeological system, and the distribution of radionuclides in the biosphere and shallow geosphere, together with assumptions about climate state and sea levels. Geology and hydrogeology are a major element but depend on the availability of relevant information and its interpretation.

B.59 Attribute 18, Post-closure - safety to individual, is based on estimates for the annual dose that the most exposed individual will receive from a naturally evolving repository. Figures were provided by UKAEA members of the MADA group but Nirex acknowledges that considerable uncertainty attended the assessments of annual dose at most of the sites. The group expressed 90 per cent intervals of confidence around an initial best estimate of individual dose caused by each site. Base case dose estimates, together with equivalent preference scores, are given in NRX/18/4. The preference scores were based on a non-linear value curve, which I discuss in paras. B.64-69 below.

B.60 Attribute 19 is Post-closure Safety to Society in the period to 100,000 (10^5) years. The preference scores were based on Collective dose received by the population but as only one site was estimated to produce any significant dose at all in the period, every site was given a preference score of 100 except No.13, Offshore East which had a score of nil. When that site was eventually dropped the weight on Attribute 19 became irrelevant. However I do not disagree with the principle on which it was applied and weight assessed in the first instance.

B.61 The CASCADE study of the shortlisted 12 sites carried out by Nirex/UKAEA produced estimates of collective dose over 10^5 years ranging from 2 man-Sv for BUSC sites, to 40 man-Sv for Sellafield B, to 700 man-Sv for a small island environment, [COR/501 table 5.2]. Nirex, quoting RWMAC annual reports [GOV/411 para.2.20(ii) & GOV/406 p.51], suggests these can usefully be compared with a collective dose from natural background radiation to the world population in the same period of over 10^{12} man-Sv. Even compared against a local population each receiving a typical UK natural background dose of 2.2mSv/y these collective doses are exceedingly small.

B.62 Attribute 20 is the long-term Post-closure Safety to Society over the period 100,000 to 100 million (10^5-10^8) years. The preference score is based on the supposed collective dose received by the designated population over that period. However its estimation involves so many uncertainties and major assumptions that it is questionable whether realistic quantitative calculations can be made for such extreme future times. I would agree with the MADA team in assigning a low weight to this attribute. In any event if compared against natural background radiation dose, all long term collective dose estimates associated with the 12 repository options are very small.

B.63 If the geological criteria used in the site selection process had been applied rigorously and consistently in reducing the initial nearly 500 potential sites to the final 12 then it should have been thought with some confidence that all the shortlisted sites would have relatively favourable geology contributing to promising radiological safety estimates. On that basis I am of the opinion that the geologically related attributes specified by the MADA team were chosen in a realistic and constructive way, and that the relative weights as between them were not unreasonable at the time. Although a favourable geological setting is vitally important to the suitability of a potential repository site, the weightings were not intended to indicate the absolute importance of a particular attribute but instead represent the relative importance of a difference in one compared with a difference in another. I do not believe there was a need for a geological node in its own right, nor that specific geological criteria such as structural simplicity or seismicity should have been recognised as relevant attributes in this particular MADA, because such matters should have been used as discriminators or eliminators during the previous stages of the process. On the other hand it is vital to understand that the base case weightings were not dealing fully with the underlying uncertainties.

Attribute 18 safety value curve and weight given to 'safer' sites

B.64 It is conventionally assumed that at the low, gradual environmental dose rates that might be involved with leakage of radionuclides from a repository there is a simple linear relationship between exposure to dose and incidence of death or serious health effect. [HMP/1/1 & GNP/1/3].

B.65 It might therefore be thought that the weighting factor should reflect this. However the possible dose rates under consideration cover numerous orders of magnitude and involve some very small numbers. A simple straight line graph covering the expected range and plotted against natural axes would give little useful discriminating power at lower dose/risk levels. On the other hand, a straight line plotted against the logarithm of dose (a simple log-linear graph) would give a disproportionate variation in weighting to low dose/risk values. In principle therefore, I accept the general form of the curve adopted by Nirex for risks lower than the 10^{-6} target [NRX/18/6 fig.2], which is a compromise between the two, based on professional judgment.

B.66 However I would say that it was not logical to assign a preference value of zero to the dose thought to correspond to the 10^{-6} post closure radiological risk target, and for all higher doses also to rate a score of zero. The precise shape of the graph adopted by the MADA team creates a large difference between a site that just meets 10^{-6} and one that is only slightly better in terms of calculated risk: a site just meeting the target would rate a preference score of nil whereas one estimated to cause half the dose and pose half the risk would receive a preference rating of about 35 out of 100. (A dose and risk of one tenth would score 75 and one hundredth would score 99.) By imposing a cutoff at 10^{-6} the scale precludes testing of the sensitivity of this attribute or the use of its discriminatory power for sites whose estimated dose effects fall into what is now called the Tolerability of Risk zone (10^{-6} - 10^{-5}).

B.67 In fact sites did fall into this zone on the MADA group's estimates. At the time of this exercise an individual risk (of death) of 10^{-6}/y was thought to correspond to an annual individual dose of 0.1mSv (10^{-4}Sv). Even on base case assumptions, site 13 was estimated to give a maximum annual individual dose of 2 x 10^{-4}mSv [NRX/18/4], equivalent to a risk of 2 x 10^{-6} and therefore not meeting the target. Under pessimistic assumptions it would appear that only 3 sites out of the then remaining 9 being considered by the MADA team - Nos.6, 7 and 12 but not Sellafield - met the risk target. For consistency with the treatment of other attributes, the preference scores and the curve of the graph should at the very least have covered the full range of estimated dose values, although it would have been appropriate for the slope of the graph to be rather flat for doses values above the target.

B.68 The Attribute 18 value curve was used to assign preference scores based on the estimated dose values associated with each site. However because of uncertainty over those values and in particular whether the leading contender in one category could be directly compared against the leader in another, the MADA group chose to keep in play at least two leading contenders in each promising category (except small islands). The attributes of 'known engineering' and 'geological certainty' may have partially addressed the underlying causes of this uncertainty but the only way in which it could be resolved would be to actually investigate sites from each of the leading geological categories and obtain more reliable factual data. If it had not been the intention to do so then the uncertainty should have been addressed by shortlisting only sites that even on a pessimistic or conservative view of the available data would comfortably meet the risk target.

B.69 I note that it was principally the relative uncertainty over the geologically based attributes 12, 13 and 18 - 'geological certainty', repository investigability' and 'post-closure safety to the individual' - that in the MADA overall pessimistic base case pushed the Sellafield B site from 1st to 5th place.

The MADA Group's use of geological factors in their final recommendations

B.70 No special significance was attached to the geology of sites during most of the MADA exercise but the link between the assessment results and geology was reintroduced by the team in drawing up its recommendations. Geology was used as a discriminating factor. Thus the team recommended that although Sites 6 and 7 are both relatively good, with only a marginal difference in overall preference, there is no need to investigate both because they are geologically similar, whereas Dounreay and Site 2, also relatively good and close in scoring, should preferably both be investigated because they are geologically different.

B.71 The MADA team recommended that at least 3 sites be investigated and offered shortlists from which 3, 4 and 5 sites could be chosen. These were drawn from Sellafield-B, sites 6 or 7 (both BUSC), Dounreay and/or Site 2 (coastal and inland hard rock respectively), and Site 3 (a small island) in various combinations which consciously aimed at carrying forward locations from differing geological environments. Otherwise, on a straightforward representation of the preference scores the shortlists would perhaps have been drawn from Sellafield B, the three BUSC sites (Nos.6,7 & 8) and small island Site 3.

B.72 Pairing of sites was done, not only in making the final recommendations but at a late stage in the analytical work. This is a reasonable approach if the pairings are from similar geologies and the intention is to keep a variety of geological environments in play. The objective would be defeated if the sites actually selected for investigation did not reflect that variety. It would also be reasonable to expect that if a first choice site became unavailable or after early investigations was clearly unlikely to prove geologically satisfactory then attention would revert to the reserve site.

B.73 In each of the recommended shortlists, BUSC Site 7 was paired with Site 6 but suggested as the second choice because it scored slightly less well. However the third BUSC site, Site 8, was itself kept in reserve as a surrogate for Site 7 because of similar scoring and was therefore not carried into the final pool. Hence the three well-scoring BUSC sites were condensed into one. Likewise Site 4 was kept in reserve for Site 3, the other small island, being so similar in almost all scores and sensitivity analyses. It too was not considered in the final list. Dounreay and Site 2, both in the broad category of hard rock locations, were considered as alternatives unless investigations could extend to 5 sites, in which case the geological differences would warrant examination of both.

B.74 On completion of the MADA sifting process the Nirex Board chose 3 sites. The combination chosen was not drawn from the MADA group's suggested list if only 3 sites were to be investigated, but all 3 were in the recommended list for an investigation of 5 sites. The MADA group's suggestion for 3 sites would have been Sellafield B, plus one of a pair of BUSC sites, plus one of a pair of hard rock sites. The Nirex Board actually selected Sellafield B and both of the hard rock sites - Dounreay and Site 2 - but no BUSC site.

B.75 Soon afterwards, Site 2 was dropped as a location for early investigation due to proposed designation as a SSSI. However because it had been paired with Dounreay there was then no logical reserve site to fall back on. Nirex did not pursue the investigation of differing geological environments by substituting a site from another category.

B.76 Greenpeace argues that the introduction by the MADA group of geological discriminators at the very last stage of their work instead of feeding revised weightings back into the full process undermined the whole exercise. This highlights the difficulties of reconciling the discrimination-between-differences approach on the one hand with both the fundamental importance of geology to the safety case and the underlying uncertainties on the other.

B.77 In compiling the specific list of 12 sites to be considered in detail by the MADA team Nirex consciously kept different environments in play because of the difficulty of comparing and ranking locations from different geological categories and to minimise the risk that a promising site might be discarded. This same consideration appears to me to be no less valid at the end of MADA and would justify the MADA team's compiling a shortlist drawing on sites from different environments, but the logical next step would be the investigation of at least the leading candidate from the most promising two or three environments. It is true that the figures used by the MADA team were revised shortly afterwards as a result of the CASCADE appraisal but no new site-specific information was being sought to address limitations in the underlying geological data and it has not been argued by Nirex that the new figures had eliminated the difficulty of comparing one generic geological setting with another.

B.78 I regard it as a significant shortcoming of the final selection of sites to be physically investigated that no representative of the BUSC category was included, the one geological environment shown consistently to score well on a multi-attribute approach and appearing to be intrinsically good in terms of radiological safety, and that no direct ground investigation of a BUSC site has been carried out for comparative purposes, if only to the same limited extent as at Dounreay.

B.79 Specifically, since geology was used as a discriminator in the final recommended shortlists, it would have been appropriate for the MADA group to have placed Site 6 above Sellafield B in each of the lists. On the base case, the main factors in Sellafield's favour were transport costs, repository operating costs, local experience and transport capital cost but Site 6 scored best on all but one of those attributes that have a close relationship with geology: known engineering, geological predictability, investigability, and post-closure individual safety. (It scored a little less well on resource sterilisation.)

B.80 There is a strong case for the selection of a BUSC site for detailed investigation. At the MADA stage, and even after the CASCADE revision of the figures, the BUSC sites appeared to be more than an order of magnitude safer than Sellafield B.

B.81 In relation to the dispute between Nirex and Cumbria over the promise of BUSC sites in central or eastern England, a paper quoted by Nirex in support of its view [NRX/14/4] describes evidence for a stable Midlands 'microcraton' (a fragment of continental crustal block) underlying the triangular area between Swansea, Derby and the Thames Estuary, and a probable concealed fold belt east of the microcraton. The microcraton was an area of stable deposition and one that has remained structurally stable over a major period of geological time since the Cambrian. The information in this paper suggests to me that there are areas on the microcraton where the basement rocks are of favourable types, at accessible depths and not severely folded or faulted, and where the overlying sedimentary strata are similarly lithologically and structurally favourable for a repository location.

Revised dose estimates following the MADA exercise

B.82 The scoring of post-closure radiological safety attributes 18-20 in the MADA exercise was based on individual and collective dose estimates said by Nirex to represent the best currently available information from the preliminary post-closure performance assessment work undertaken for the various repository concepts. However subsequent to the MADA recommendations and prior to publication of the PERA report [COR/501] further post-closure risk assessment calculations became available. New concept-specific assessments had been made for the small island and 'offshore hard rock deep' options and risk estimates for all other options were revised. The estimated annual individual doses resulting from hard rock environments (Dounreay & Site 2) were revised slightly downward, otherwise small island values were revised upward by about 3-fold, BUSC sites upward two-fold, and Offshore West (Sites 11 & 12) also upward. The remaining four sites, including both Sellafield options, remained unchanged. [NRX/12/14 table 1, summarising NRX/18/4 (MADA) & COR/501 table 5.2 (PERA).] Nirex has explained that the relatively large changes in the small island and offshore hard rock/deep water option occurred because the MADA inputs for these options had been based upon judgments rather than calculations, and changes to the calculated dose for the BUSC and low-relief/hard rock options were a consequence of detailed corrections to the numerical modelling in finalising the CASCADE exercise [NRX/12/14].

B.83 The estimated annual individual dose for Sellafield B (Site 10) stayed at 0.02mSv (2 x 10^{-5}Sv) between MADA and publication of PERA. However, as shown by PERA Table 5.2, the original peak annual individual dose calculated for Sellafield B using MASCOT was only 0.0003mSv. This was revised upward almost 70-fold to 0.02mSv for use in the MADA calculations to allow for site specific uncertainties and 'other processes' not included in the MASCOT models. The equivalent figure for the seaward dipping sediments generic type was similarly revised upward by a factor of 20, from 0.001 to 0.02mSv.

B.84 Despite the revisions to dose estimates shortly after the MADA exercise was completed, the effect of the changes on the MADA scoring and ranking would have been minor. Individual site preference in terms of Attribute 18 remained virtually unchanged except that sites 3 and 4, the small islands, dropped from joint 8th (penultimate) place to joint 11th (last) place. Sellafield B remained in joint 5th and Dounreay in joint 8th places on post-closure radiological safety to the individual. [NRX/12/14 table 1] In terms of overall MADA site preference, although some individual site scores would have altered by a single percentage point the overall site ranking would have remained unchanged. [NRX/12/18 table 5.3]

B.85 What has been highlighted is that not only have dose estimates been revised for individual sites but the recognised dose-to-risk conversion factor has also been revised and has a much more dramatic effect on all the results. At the time of MADA all sites supposedly met the 10^{-6} target for risk of death under best-estimate conditions except Site 13, Offshore East, which was twice the limit; now, the majority of shortlisted sites would no longer meet the 10^{-6} risk target for deaths and serious hereditary effect. Following the recommendations of ICRP 60, HMIP's Draft Guidance [HMP/1/1, para.6.10] defines a risk factor of 0.06 per sievert for the induction of fatal cancers and serious hereditary effects. If the revised dose figures published in PERA are converted to peak individual risk on the basis of the 0.06 factor, the following figures emerge:

Site 12	$3.6x10^{-8}$	) meet target
Sites 6,7 & 8	$1.2x10^{-7}$	)
Sites 5,9 & 10	$1.2x10^{-6}$	)

Sites 1 & 2	$3.6x10^{-6}$	) fail target
Site 11	$6.0x10^{-6}$	)
Sites 3,4 & 13	$1.2x10^{-5}$	)

B.86 Thus, using current criteria, it can be said that both Dounreay and Sellafield B (Sites 1 and 10) would have been judged not to meet the risk target; that Offshore West Deep (site 12) and the three BUSC sites (6,7 & 8) all comfortably meet the target; and that the BUSC sites are estimated to be an order of magnitude safer than Sellafield B in terms of peak dose and post-closure radiological risk to the individual.

B.87 It is understandable that there should have been some adjustment to the dose calculations. This is a continuous process that would be expected each time new and better data become available. However the biggest change has been in the implications of the dose/risk factor. If the new guideline figure had prevailed at the time of site selection and sieving prior to MADA it may well have influenced the selection of sites for shortlisting. If taken into account in the MADA exercise it is likely to have resulted in greater weighting being given to Attribute 18 and possibly also Nos.19 & 20, and there would have been a different value curve giving greater emphasis to figures meeting the new dose target.

Switch from Sellafield B site to the present PRZ

B.88 The Sellafield B site as first selected and considered in the MADA exercise was the Pelham House School Estate near Calder Bridge, about 3km inland. The repository would have been in the BVG basement [NRX/12/11A]. The geology of the neighbourhood was known from previous boreholes, mostly associated with iron ore exploration. Below a thin cover of glacial deposits there are Permo-Triassic rocks to 530m depth, then 25m of Carboniferous Limestone to 555m, overlying the Borrowdale Volcanics [COR/501 table 8.1 & fig.8.2]. Subsequent drilling and geophysical investigations by Nirex have confirmed this picture [eg see 'Site' maps in COR/518 vol.1].

B.89 Nirex has explained [NRX/12/11A] that for the purpose of preliminary risk assessment in 1988 the Carboniferous Limestone was assumed to have a hydraulic conductivity higher than the BVG but lower than the Triassic sandstones so its properties would not have significantly influenced the results, but that subsequent geological advice began to suggest that the Carboniferous Limestone was potentially karstic (i.e. contained solution features) and could offer a hydraulic connection to present day pumping of mineworkings to the north. The search area was therefore shifted south of the areas thought to be underlain by the limestones.

B.90 I am surprised by the initial choice of a site where the limestone is present. The karstic dissolution features of Carboniferous Limestone had led the 1986 study by Chapman & others to caution against siting a repository in basement rocks below these limestones [COR/614 & B.33(c) above] and the karstic nature of the West Cumbrian and Furness Carboniferous Limestones was well known to geologists before 1988. Nirex now also rightly says that the Carboniferous Limestone should be avoided because the general presence of iron ore bodies in the district increases the risk of future human intrusion. I do not consider that the tentative detailed conclusions of COR/522, v.1, s.5.4 about local cavities and hydrogeological units detract from these basic points.

B.91 Attention began to shift to the locality of Borehole 2 later in 1989, and by 1992 the current PRZ had been substantially defined [COR/504 fig.4]. Except for the presence of the limestones, the general geology of the Pelham House and PRZ areas are quite similar: a typical depth to the BVG is 555m at the former and about 525m near the proposed RCF shafts; both sites have similar geological complexity, with 6 or 7 significant faults (of 50-75m downthrow) cutting the strata in the Pelham House estate compared with a similar number (though often with larger throw) in the PRZ. However the presence of the limestone could have made a substantial difference to the Sellafield B risk calculations. The 1988 PERA calculations assumed a Carboniferous Limestone hydraulic conductivity of $1x10^{-8}$ m/s [COR/501 table 8.2] but Nirex 95 modelling suggests a figure for the rock mass in the immediate vicinity of a mine of about 1×10^{-6}m/s [COR/522 vol.2, table 5.4]. It is reasonable to assume that if the earlier calculations had made some allowance for enhanced limestone conductivity then higher values of calculated risk would have emerged.

Scope for varying the repository location within the PRZ

B.92 The boundaries of the PRZ as now defined reflect current land ownership but were drawn essentially on geological and hydrogeological grounds. General limits to the siting of an actual deep waste repository are set by the gross geological structure. Within those there would be additional constraints imposed by detailed geology and hydrogeology and the presence of excavations and perhaps also drillholes associated with the RCF. In 1991 a possible repository site was assumed for transport assessment purposes to be in the PRZ just east of Fleming Hall Farm [NRX/12/11A, attached briefing note]; and then Nirex 95 assumed the notional repository to be rather further to the east [COR/522, v.3, Fig.6.1].

B.93 The overall limits within which a repository could be sited in the vicinity of the PRZ are quite tightly constrained:
(a) the BVG is the potential repository host rock but the rule of thumb adopted by Nirex is that there should be a minimum of 200m of BVG cover above a repository (the uppermost 100m of the BVG being thought to have somewhat elevated hydraulic conductivity), so the practical upper limit would be a surface 200m below the top of the volcanics. The overall dip of the strata is towards the south-west so this nominal upper surface falls in the same direction, from what I calculate to be about 525m below OD at the northeastern edge of the PRZ (a depth of about 625m from the surface), to about 675m bOD at the southwestern edge (say 710m depth), and 725m bOD (a depth of perhaps 765m) below the southernmost corner. (These may be compared with the preferred RCF depth of 650m bOD.)

(b) The lower limit has been taken as a depth of 1000m below ground level, below which rock stresses and temperatures, and consequential excavation disturbance, are considered to become too severe for practical and economic repository construction. This depth approximates to a level of 900m bOD.

(c) In terms of plan position the northwestern limit is defined by the presence of Carboniferous Limestone immediately overlying the BVG, between it and the general cover of sandstones. The need to avoid the limestones is due to the intrusion risk and to their anticipated enhanced hydraulic conductivity along fractures because of solution processes. The limestones extend to within about 150m of the NW side of the PRZ.

(d) the southwestern limit is the Fleming Hall Fault, a persistent NW-SE trending structure that downthrows the BVG rocks and overlying strata towards the southwest by as much as 355 metres. It is more usually referred to as a 'fault zone' because of the numerous subordinate faults branching from it or running sub-parallel. The main fault (at the depth of the BVG) lies 400-600m beyond the southwestern margin of the PRZ and more or less parallel to it. Not only is the BVG much deeper and less accessible west of the fault zone but the Carboniferous Limestone is present and, for the reasons just stated, is also to be avoided;

(e) similarly the southeastern limit is the Seascale Fault Zone, a major WSW-ENE trending structure comprising a number of individual faults which cumulatively displace the Borrowdale Volcanics and overlying strata southward by over 350 metres. The closest significant fault within the fault zone (at the depth of the BVG) is 400m or so southeast of the PRZ.

(f) the northeastern limit for a potential repository has been taken as the National Park boundary, but in any event in that direction the depth to the BVG and thickness of the sedimentary cover reduce steadily towards the BVG outcrop only 2½km away. The nearer the outcrop the more direct will be the groundwater recharge.

B.94 In summary then the geological constraints recognised by Nirex in defining a maximum repository zone in the vicinity of Longlands Farm are the Fleming Hall Fault Zone to the southwest, Carboniferous Limestone to the northwest, lack of sedimentary cover to the northeast, and the Seascale Fault Zone to the southeast. I agree that these are all logical boundaries. They define an area about 2400m NW/SE by 1500m SW/NE, and between a nominal highest level of 650m bOD and nominal lowest level of 900m bOD. However within that area there are further constraining features:

B.95 Current hydrogeological modelling assumes that the Fleming Hall and Seascale Fault Zones are significant hydrogeological features with associated enhanced hydraulic conductivity (primary structures designated as Type III features in the Nirex classification system). In consequence Nirex assumes that a repository should avoid both these fault zones.

B.96 However even the supposedly secondary faults have characteristics that make me think that any prudent repository developer would wish to avoid them in his repository design. Some of these faults, whilst not having a great longitudinal extent, have considerable local vertical displacement in the vicinity of the PRZ. An indication of the current understanding of the magnitude of the vertical displacement (or 'throw') of the various faults as they affect the BVG rocks can be obtained from the structure contour maps in the Nirex report on the 3-D Geological Structure of the PRZ [COR/530].

B.97 It can be seen that, on current understanding, faults 2, 3, 205 and 207 locally have throws well in excess of 100m and a number of other faults have displacements approaching 100m, figures that are not much less than the major Fleming Hall and Seascale faults. Indeed Fault 2 not only has a significant downthrow but appears to meet the criteria to be defined as a Type III feature, having a trace length in excess of 5km.

B.98 A large vertical displacement on a fault means there is a likelihood that at any particular depth the rocks on opposing sides of the fault plane will belong to different 'members' of the BVG and of quite different lithologies and perhaps also hydrogeological characteristics. The fault zone itself may have adverse hydrogeological properties. On the basis of the relatively small number of Type II and Type III fault intersections in the boreholes to date, Nirex has found no direct relationship between the magnitude (displacement and/or length) of a fault and its hydraulic properties but a prudent assumption would be that the larger the throw and the more sinuous the fault plane the more likely it is that there are at least portions of the fault-disturbed zone with higher hydraulic conductivities.

B.99 On the basis of present knowledge about the hydrogeology of the faults, if consent were to be sought for a repository in the PRZ, I can see no reason why Fault 2 should be treated differently from the Fleming Hall and Seascale fault zones and as such it would be logical for Nirex to seek to avoid it. It would also be desirable to avoid each of the other larger-throw faults. However these larger-throw faults form a complex three-dimensional pattern. Whilst they appear to broadly trend NW-SE and incline towards the northeast, the fault planes seem clearly to intersect and diverge and sometimes die out within the PRZ. The blocks of rock between these larger faults must therefore be variable in width. In the BVG the maximum width between significant faults seems to be less than about 650m and typically only 200-500m. [See for example COR/501 drg.010054, structure on the Top Basement.]

B.100 The notional repository layouts in the BVG adopted by Nirex for the purpose of hydrogeological modelling have assumed vaults of over 500m in length [eg COR/522 vol.3 fig.6.1]. If Type III structures and larger-throw faults currently classified as Type II features are to be avoided, they would significantly affect the layout and orientation of repository tunnels and vaults. It would be difficult to find any block of rock in the target BVG volume where 500m long parallel galleries could be driven in NE-SW directions (the preferred orientation for stability and hydrogeological reasons) without cutting across one or more of these faults. However, although the notional repository layouts comprise neatly geometrical arrangements of galleries in a particular orientation, in practice there would be plenty of scope for variation, as is commonly done in mining operations to suit geotechnical conditions. Although to have irregular layouts would make the computer modelling of the system for the purpose of PCSAs that much more difficult, the target volume of the BVG in the PRZ is sufficiently large that I consider it would be possible to find one or more sufficiently large fault-bounded blocks that the requisite number and volume of vaults could be fitted in somehow.

B.101 Groundwater and radionuclide transport modelling by Nirex has shown that the safety case for the Sellafield PRZ is sensitive to variation in the precise repository location. Nirex has indicated therefore that its first objective would be to optimise the location and layout of the repository within the 3-D space of the BVG in the PRZ having regard to the faulting, and the variations in physical, hydrogeological and other relevant characteristics of the rocks. There appears to be a relationship between the various members and formations in the BVG and the occurrence of flow zones, so for example in the vicinity of the proposed shafts parts of the Longlands Farm Member, which is the preferred host for the RCF, have relatively more flowing features and the Town End Farm Member almost none. There is also an apparent reduction in flow zone hydraulic conductivity with depth.

B.102 The presence and location of the RCF will have some constraining effect on the available volume in the PRZ for a repository. However in principle I do not agree with FOE that the RCF damage zone and stable base conditions area represent very serious constraints, provided the design and execution of the RCF operations expressly take account of possible repository construction close by. Indeed, to be useful the RCF needs to be close enough to the eventual repository location to have characterised the same general units of rock.

B.103 Nirex has deliberately sited the RCF in the north-eastern sector of the PRZ and claims that this would have specific advantages for utilisation by the repository, for drainage, and in connection with ventilation and emergency access. The excavation, probing and experimentation would be predominantly in the same member of the Fleming Hall Formation of the BVG so that the scientific and technical information gained would be most appropriately applied to a repository in the one group of rocks. The map of the strata at the level of 650m bOD [COR/530, drg.010067] indicates that the preferred Longlands Farm group of rocks are relatively extensively distributed across the southeastern quadrant of the PRZ at that level and therefore it ought to be possible to find enough space within which to construct both an RCF and a repository in that area if that depth and stratigraphical member were thought to be the most appropriate combination. However on the basis of borehole testing to date, Nirex has established that other, deeper parts of the BVG sequence appear to show better hydrogeological characteristics.

C SCIENCE & TECHNICAL PROGRAMMES

Main components of programmes to date

C.1 I note that from mid 1991 the Nirex Science Programme has been directed at establishing the suitability or otherwise of the Sellafield site to host the deep repository [eg NRX/11/1 p4] and to support a detailed post-closure performance assessment has involved two broad areas of work: firstly the Site Characterisation Programme to investigate the surface and subsurface characteristics of the potential site; and secondly the Nirex Safety Assessment Research Programme (NSARP) which includes research on fundamental physical, chemical and biological processes affecting the safety performance; plus modelling and methodological development [eg COR/526, Introduction].

C.2 The multibarrier concept of the possible repository means that parallel lines of research and assessment are required relating to the waste and the engineered systems, the geosphere, and the biosphere. The volume and multi-faceted nature of the work means that Nirex makes extensive use of specialist external contractors and agencies and the reports are commonly the product of collaborative, multi-disciplinary teams.

C.3 Earlier work concerning possible shallow repository sites at Elstow, Bradwell, Fulbeck and Killingholme, and a disused mine site at Billingham [NRX/11/1 'November Note' s.2] is of little practical relevance to the Sellafield area and a deep waste repository concept in undisturbed deep hard rock. The Dounreay investigation [described in COR/506], although terminated after only two drillholes and some geophysical surveys, will undoubtedly have assisted in the development of techniques and assessment methods.

C.4 It is evident that the duration, intensity and breadth of the Nirex scientific and technical programme, concentrated on Sellafield alone, has expanded enormously compared with what Nirex envisaged after the first few drillholes and 2-D geophysical surveys had been completed [NRX/12/2 Nirex letter to Cumbria Chief Exec., 21.1.92, paras.4,6,7]. It seems to me that in almost every important aspect the task has proved to be bigger and more involved than had at first been envisaged, and that a greater depth of knowledge and understanding has been required to carry out the necessary assessment and modelling. Much work has needed to be done to appraise the basic stratigraphy and geological structure of the district, and the hydrogeology, geochemistry and hydrochemistry: the long timescales appropriate to the types of waste to be disposed of has meant the need for greater attention to long term climatic and geological processes: studies commissioned by the regulators to develop methodologies for dealing with eventual repository applications have highlighted differences of approach: and weaknesses have been identified by bodies such as the Nirex Review Panel and the Royal Society in the scope of research that have been addressed.

<u>Site Characterisation Work</u>

C.5 The site characterisation programme at Sellafield has comprised studies to characterise the geology, hydrogeology and geochemistry by means of surface geological survey and geophysics, by borehole surveys and down-hole measurement, and by sampling and laboratory analysis. Because understanding of groundwater flows in what are essentially fractured rocks is crucial to a repository safety case, much effort has been directed toward establishing the location, orientation and connectivity of faults and the three-dimensional geometry of joint systems, attempting to relate the pattern of conductivity to the rock sequence and to the faults and joints that cut it, and generally characterising the groundwater system.

C.6 Nirex has made studies over areas much wider than the PRZ, at scales designated as Site (about 50 sq.km), District (600 sq.km) and Region (about 4000 sq.km). Although the Region may seem very large it is necessarily so having regard to the influence of factors such as present and future groundwater flows, and tectonic movement and seismicity. Regional surveys have been made of the bedrock geology and superficial cover (mostly Quaternary glacial, marine and lake deposits) by re-mapping of surface exposures, re-interpretation of available sub-surface data (mine plans, borehole and geophysical data), and shallow boreholes and pits. The mapping of the Quaternary deposits has been significantly more detailed than previously.

C.7 An impressive range of geophysical surveys and studies have been carried out on a regional and local scale [NRX/14/13, s.A.2.1 & Table A.1, & COR/605 s6.3], many commissioned by Nirex but on the wider scale including BGS and commercial surveys, particularly offshore. In general there have been closer spaced traverses or point observations in the vicinity of the PRZ [COR/518, v.1, Section 2 drawings]. Most of the geophysical techniques, supplemented by aerial photography and imaging, are fairly conventional but a number of less conventional methods have been tried, including various electromagnetic techniques, which I believe are more appropriately thought of as research methods rather than practical survey tools.

C.8 An important area of work has been a 3-D seismic reflection trial survey across the greater part of the PRZ [COR/518, v.1, drg.010011]. The method uses more closely spaced survey lines than conventional 2-D traverses and gives higher resolution interpretation of geological structure at depth. [NRX/14/13, s.A.2]

C.9 Nirex has carried out deep drilling at 22 localities in the Sellafield district, of which 12 holes are in the PRZ. I note a general objective to identify the geology and hydrogeology in a NE-SW direction through the PRZ, following the broad dip of the strata, and secondarily in a NW-SE direction through the PRZ along the strike of the rocks. The stated purpose of the individual holes [NRX/14/13, Table A.3] indicates a logical progression of the investigation: firstly a general reconnaissance in the neighbourhood of Sellafield Works and Longlands Farm (holes 1/1A, 2, 3 & 4), then a wider pattern to obtain a better understanding of the geology and hydrogeology in the intervening area (holes 5, 10A, 10B, 10C & 12A) and northwestward across the River Calder where the Carboniferous limestones are of significance (7A, 7B & 14A). The Works-PRZ line was extended to investigate the groundwater recharge area to the northeast (nos.8A, 8B & 9A). A hole to the southeast of the PRZ (11A) and holes to the southwest (13A & B) were sunk to investigate areas of anticipated thick Permo-Triassic cover. The later holes of the PRZ, RCF and RCM series represent a closing-in on the target area for the RCF and preferred repository location with the objective of proving the three-dimensional geology, characterising the main geological formations and investigating faults, of carrying out groundwater monitoring, sampling and testing, and carrying out cross-hole testing of various types. A number of the holes, particularly the later ones, have been angled or deviated from the vertical to provide better information on faults and sub-vertical fractures. [NRX/14/13, s.A.4.2].

C.10 The rock core has been closely logged and subjected to a wide range of physical, mechanical, petrographic and geochemical testing, much of it conventional but intensive and to a high standard, so that the maximum information has been squeezed out of the available material [NRX/14/13, Table A.4]. The boreholes have also been subjected to detailed downhole geophysical logging using a wide variety of wireline logging tools as an aid to determining general rock types and properties, discontinuities, groundwater inflows and various basic parameters [ibid., Table A.6]. Some of the techniques are long-established and standard but the range of tests and the equipment used seems to me to represent the highest quality available in the petroleum and metalliferous mineral exploration industry. There are no obvious omissions in the range of techniques that have been applied.

C.11 Seismic surveys have been made within and between boreholes. Particularly interesting have been the detailed cross-hole ('seismic tomography') surveys that have been tried on an experimental basis between 6 pairs of holes within the PRZ [NRX/14/13, s.A.6.3-5]. These permit an interpretation of geological reflective features in a 2-D slice of rocks between the holes to a vertical accuracy of perhaps 10m or so and augment the vertical seismic profiling where seismic waves generated at the surface are detected by receivers progressively lowered down each hole.

C.12 It is necessary to consider the surface hydrology and shallow hydrogeology on a regional basis in order to understand and model the regional water balance. Nirex has studied the surface and groundwater catchments of the Rivers Calder and Bleng, extended northward to the mining areas of Beckermet and Egremont where there is heavy groundwater abstraction and southward to an area of thick glacial deposits [approximately defined on COR/521 figs.3.6 & 4.12 except that the Bleng catchment needs to be estimated]. It has been collecting the usual relevant data by monitoring watercourse and spring flow and water chemistry; and collating records of existing boreholes [NRX/14/13, s.A.3 & NRX/5/1] and groundwater abstractions [COR/521 p4-14].

C.13 Reliable groundwater head records are essential to groundwater flow modelling, and to establishing baseline conditions against which the hydrogeological impact of RCF construction can be assessed. Borehole monitoring data over an extended period are available for only a small proportion of all the holes in the district and wider area of West Cumbria, but the numbers are large enough to be useful, a total of about 100 holes in West Cumbria with more than 5 years records, of which there are 16 boreholes in the Sellafield district with data from 1974. However monitoring has been predominantly in the sandstones and glacial drift deposits with sparse information on the limestones and only recent Nirex data on the BVG [COR/501 4.4.1-5].

C.14 Groundwater samples from the deep boreholes, springs, rivers and surface rainwater have been analysed for a wide range of fairly standard chemical parameters [NRX/14/13, A.8.1 & Table A.9], including representative major and trace ions, various naturally occurring isotopes both stable and radiogenic, various reactive and inert gases, and pH, Eh, alkalinity and electrical conductivity. A rigorous quality assurance system appears to be in place for this and all other Nirex chemical analytical work.

C.15 The Eh (the 'redox' or reduction-oxidation potential) of the groundwater is important because of the control it exerts over chemical reactions within the water system, and reactions or equilibrium between groundwater and rock surfaces, waste or repository barrier materials with which the water comes in contact. However the reliable determination in the laboratory of the Eh of borehole water samples taken at great depth is very difficult because of the presence of drilling fluids and the steel of the drill rods and core barrel.

C.16 The use of chemical tracers in the drilling fluids has allowed corrections to be made for contamination of groundwater samples by those fluids. Although contamination had been reduced to less than 1% in a significant, and increasing, proportion of samples, even better chemical sampling will be needed to resolve some of the uncertainties of geochemistry in the BVG.

C.17 The isotope and inert gas studies are particularly relevant to estimations of the residence time (the 'age') of the groundwater. A number of time-dependent indicators have been considered: stable isotope ratios for oxygen and hydrogen ($*^{2}H$ and $*^{18}O$); noble gas recharge temperatures; tritium levels; carbon-14 results; chlorine-36 ratios; and helium levels.

Safety Programme Work

C.18 Numerous areas of work can be included under this heading, often involving the application of generic research to the Sellafield circumstance. These include, for example, climate change, radionuclide transport and uptake in the biosphere, near field evolution, aspects of gas generation and migration, and the development of conceptual and numerical models and methodologies for probabilistic safety assessment. I do not dwell on those that are not primarily related to geology and hydrogeology. Others such as aspects of Near Field Research into the engineered and chemical barriers are commented on later in this chapter.

C.19 Research is carried out by Nirex into tectonics and seismicity as part of its post-closure performance assessment in the areas of human intrusion and natural disruptive events. The work has involved monitoring of current seismic events, assembly of data on historical earthquakes, and by means of mineralogy and studies of stratigraphy and structural geology, attempting to create a chronology for earth movements over geological time, particularly episodes of faulting (with its associated seismicity). I comment on this in more detail in para.C.122ff.

C.20 Other long term processes being considered are future climate states and landform evolution. The two are inter-related. Within a time frame of say 100,000 to 1 million years the greatest landform changes are likely to be climatically induced, that is to say, sea level rises (relatively small) or falls (potentially large) marking fluctuations between global warming and major glaciations, and the direct effects of glacial ice advance and retreat. Sea level changes will obviously alter the coastlines and the respective extent of terrestrial and marine biospheres as well as affecting groundwater gradients and discharge locations. Ice advances can strip away and redeposit superficial materials and weak bedrock, changing the topography and altering the rate of infiltration of meteoric water into the rocks. Climate changes will affect amounts and seasonal patterns of precipitation and evaporation and also vegetation cover, in turn affecting runoff and groundwater flow. They will alter the natural animal and plant life as well as human habitability and patterns of settlement, agriculture and way of life. Additional comments on climate research are made at para.C.132 below.

C.21 The Safety Programme makes extensive use of models in its evaluation of post-closure safety performance, requiring much field and laboratory data in their development and application. Validation of the models requires additional independent field and experimental data against which model predictions can be systematically compared. Modelling is discussed in the next chapter.

International cooperation and input to Nirex domestic programmes

C.22 Nirex plays a leading part in international research into aspects of radioactive waste disposal. Of the various underground research facilities in which it has been a participant Nirex considers that the Swedish and Canadian rock laboratories have the greatest application in the UK. However I share the view expressed in the Royal Society report [COR/605, s.4.4] and by the principal objectors at the inquiry that none of the sites in other countries is very similar in geological setting to Sellafield. Nirex itself says that although the results of these generic experiments have been of considerable value they are inadequate for a full characterisation of the rock volume under consideration at Sellafield and there is no substitute for actual testing in a RCF.

C.23 Nonetheless work in all these facilities provides valuable experience in the development of investigation methodologies, equipment and experimental techniques, and much comparative data on rock properties and responses. Lessons can usefully be learned even from experiments and tests that have given poor or unexpected results. The Stripa work for example is generally agreed to have contributed much to the development of new methods for investigating and testing fractured hard rock and to new modelling approaches that could be applied to further work in other rock laboratories [FOE/6/15, pS.29 last para. & GNP/4/10, s.3.1]. Experiments at Äspö include comparison of rock disturbance produced by tunnel boring with that by drilling and blasting; characterisation of the zone of excavation disturbance (ZEDEX); multiple well tracer tests (MWT); and investigation of the effect of mine air on the geochemistry of the surrounding rock [COR/605, 4.3.1-4].

C.24 In addition to the direct underground work, I regard also as important and useful the associated mathematical modelling, and laboratory and other surface experimental work and testing, much of it related to fundamental chemistry, geochechemistry and hydrochemistry. These include international research projects on migration of radionuclides through the geosphere (MIRAGE), the basic validation of geochemical codes (CHEMVAL), those on colloids and complexes (CoCo), and on gas generation and migration from underground storage facilities (PEGASUS), and of particular importance the development of coupled thermo-hydromechanical models (DECOVALEX).

C.25 The international collaborative studies on natural analogues are useful in shedding some light on processes relevant to the underground storage of radioactive waste, particularly of geochemical systems and mineralogy, over geological timescales.

Data availability and elicitation

C.26 Data elicitation has been used by Nirex to define PDFs (or CDFs) for many of the parameters used in the numerical modelling of the preliminary safety case, in fact for the 21 elements considered to be of greatest interest [COR/529, p.69]. Within each 'element' it is evident that there may be many PDFs requiring to be defined. Although these have mostly been elicited by a team of specialists following a formal methodology, I note for example that many near-field sorption distribution (Rd) ratios for radionuclides and geological units were derived directly by the judgement of one or two individuals [no change from COR/605, s.8.4.1]

C.27 A good example of the variable quality of data faced by Nirex and the need to address uncertainty by the use of formal assessment to arrive at 'best estimate' values is given for the solubility of various key radionuclides [COR/529, s.3.2.1 & Box 13]. It also shows how different values can be obtained under different experimental conditions.

C.28 Nirex considers the elicitation process to be a structured and appropriate response to dealing with uncertainties in field data. It seems to me that the use of elicitation has been and is proper and appropriate, and I broadly agree that it was the only practical way of carrying out a preliminary safety assessment like Nirex 95. The PCPAs are based on numerical values for a large number of parameters (physical, chemical and expressive of human and natural behaviour), relating to the waste inventory, the engineered and chemical containment barriers, the geosphere and the biosphere. Some may be narrowly constrained but others, no matter how much data have been collected, may reflect a wide spread of values or considerable uncertainty. It is evident that much new data have been acquired even since the information on which Nirex 95 was based and Nirex and its contractors continue to acquire data from site based studies and from laboratory or other experimental work. As more and better field and laboratory data come in so it would be expected that many PDFs might be expressed within narrower confidence limits. Nevertheless the site data are limited by the practical constraints of sampling and testing in deep, small diameter, relatively widely separated boreholes. Much more data would become available if measurements could be made at close quarters on the exposed rock faces of a facility like the RCF and by probing outward from it.

Transparency, peer review and quality

C.29 The Nirex basic and site-related scientific and technical programmes have been large in scale and wide in scope and have generated many reports, papers and presentations. Nirex indicates that it has so far published more than 500 scientific reports and papers and has made available a further 1600 reports for reference. Those numerous papers published in academic journals will have undergone the usual independent scrutiny of the refereeing process. A general indication of the scale and range of Nirex's safety assessment research programme up to that date can be gained from the Nirex Bibliography 1994 [NRX/12/7] which lists over 400 publications said to represent over 1200 experiments. Much of this work involves basic chemistry of radionuclides, research into the special conditions created by cementitious repository near-field conditions, and modelling studies: very little relates specifically to the Sellafield area.

C.30 Until the run-up to the Inquiry it appears to me that the principal information specific to the Sellafield area was a series of Nirex reports published in December 1993, of which Reports 524 [COR/517, Interim Assessment on Geology & Hydrogeology of the Sellafield Area] and 525 [COR/505, Scientific Update 1993] were put forward by Nirex as examples of openness. The latter was evidently widely distributed but the former report, and supporting detailed geological reports 515-521 [listed in COR/517, v.1, pp.50-51] appear to have been available only for consultation or on loan for research. However the outline of all this geological work was presented publicly at a special meeting of the Yorkshire Geological Society in October 1993, the proceedings of which were published 12 months later [eg FOE/3/8]

C.31 I am aware that a further significant seminar, organised by Nirex and concentrating on the hydrogeology of the Sellafield area, took place in London in May 1994 under the auspices of the Geological Society although the proceedings had not been published by the close of the inquiry. A further conference (for paying delegates) was held in London in May 1995, at which Nirex presented up-to-date review papers on the geology, hydrogeology and hydrochemistry of the PRZ and wider Sellafield area [COR/601-604], and waste packaging [GNP/3/2], but papers were also presented by independent researchers [eg GNP/3/6].

C.32 Much new information has been brought forward since the publication of the Royal Society report [COR/605]. Indeed it appears to me that the Inquiry - and the public at large - has had available to it much more information than the study group or other observers such as RWMAC, not only the 'Core' documents but the supporting documents available in the Greengarth library of Nirex.

C.33 With the publication of the S/94 series [COR/507-514] and in particular Nirex 95 and the S/95 series of reports [COR/518, 518A, & 522-530] Nirex has made a notable advance in starting to pull together all the individual pieces and areas of research so that a more integrated and coherent story is emerging. These reports, and similar contributions by Nirex personnel and contractors to conferences and journals, seem to me to exhibit a good degree of openness in the best scientific and engineering tradition, in general setting out the underlying data and assumptions, identifying weaknesses, uncertainties and difficulties as well as areas of success and promise, and identifying matters requiring further investigation. The quality of presentation of documents is generally excellent.

C.34 A factor contributing to the delay in publishing results has been the rigorous application of quality assurance procedures by Nirex. It is evident that reports go through a number of draft and interim stages before they are approved for release to the academic community or public. Documents are classified as Commercial in Confidence until they have been through quality checks and review although only a small proportion of the work and results appear to have what would usually be thought of as commercial value (an example being the details of the Nirex Reference Vault Backfill for which a patent has been applied). Although QA procedures can slow the pace of publication, I consider this is a small penalty to pay if it leads to quality, accuracy and completeness of interpretive reports. However it seems to me that the release of factual data from site investigations and laboratory work has often been delayed for similar reasons, awaiting presentation in a polished report. I welcome Nirex's assurance that preliminary site results from the proposed RCF science programme would be released almost as soon as they are obtained.

C.35 Much of the Nirex work can properly be described as erudite scientific and technical research so it is natural and proper that the results have tended to be disseminated through the channels of learned societies and professional institutions, thereby reaching the international community. Nirex says it does not seek to sustain academic debate for its own sake, limiting independent review of work critical to radiological safety to scrutiny by experts not directly involved with the piece of work concerned. However it could be argued that by involving so many outside parties, including the BGS, numerous university departments, leading independent consultancies, international agencies and parallel overseas organisations, the Nirex programmes are being subjected to continuous wide scrutiny and are bringing the best and most varied thinking to bear on the problems. For example, COR/517 [Interim Assessment of the Geology and Hydrogeology of the Sellafield Area] represents the combined efforts of eight organisations external to Nirex, including five private sector consulting firms. It seems to me that Nirex has been relatively good at publishing the results of individual pieces of research and exposing detailed aspects of its work to independent scrutiny, however it is not evident that it has exposed its overall scientific and technical strategy to peer review or wider public scrutiny.

C.36 Taken overall I share the view expressed by the Royal Society and Nirex itself that the Sellafield investigation has involved one of the most comprehensive and technically sophisticated pieces of geological characterisation ever carried out in the UK and that the individual items of research and investigation are of high quality. I agree that Nirex is at the forefront of science for much of the geological and repository near-field research: however it needs to be because of the scientific and technical challenges that it faces both with the disposal of long-lived intermediate and low level radioactive wastes in general, and with the Sellafield site in particular.

Current understanding of scientific and technical issues

Groundwater Flows and Hydrochemistry

C.37 Heads and Flows: Nirex has been considering the geology and hydrogeology at a Site, District and Regional scale [COR/518, v.1, drg.010006 & paras. C.6 & 12 above]. Reliable water levels and pressure head data are available for only a small proportion of the many boreholes and wells constructed in the region over more than a century [para. C.13]. To develop a fair understanding of the present groundwater flows as they affect the PRZ it might be sufficient to consider little more than the area of the surface catchment and a relatively short distance offshore. However in order to consider the effects of the foreseeable long-term changes in climate and topography, including glaciations and sea-level fluctuations, it is necessary to look more widely. I concur with HMIP's suggestion at the inquiry that it would be appropriate to consider recharge conditions and flows up to tens of kilometres from the proposed repository. Such an area is comparable with Nirex's 'Region'.

C.38 It is not necessary to have a uniform scatter of boreholes and other data points across the whole area of interest but enough reliable points are needed to be able to create and calibrate groundwater flow models and define boundary conditions. The Nirex programme of drilling and monitoring has been designed to give the best array of data in a 5 or 6km long NE-SW direction through the PRZ and secondarily on a similar axis NW-SE through the PRZ. It is not obvious to me that there is yet an adequate number and distribution of data points to have a good fix on groundwater heads and flows over the Site area (though Nirex itself is seeking planning permission for more boreholes) and certainly not over the District. At the Regional scale I consider it would never be possible to develop anything other than the most sketchy groundwater model because of its irregular topography and rapid changes in geology.

C.39 Monitoring of boreholes by Nirex and others has been carried out over a long enough period to establish patterns of fluctuations in head. The general data appear to support Nirex's claims to have a good understanding of the seasonal and synoptic (i.e. cyclical periodic) head variations observed in many of the holes, and to recognise trends in effective rainfall from year to year. Nirex says that once the boreholes have settled down after the disturbance of drilling, water heads in the deep BVG show only diurnal and semi-diurnal effects. I consider the monitoring period has not been long enough to show slow trends in the deep BVG, but in any event I consider it was premature of Nirex's independent hydrogeologist to declare [NRX/14/3] on the basis of data up to April 1995 that baseline conditions had effectively been restored in the PRZ boreholes when subsequent monitoring has shown continued slow drift of values in some of the holes [eg COR/518A, Borehole 8A probe P5, & Borehole RCM2 probe P2].

C.40 'Environmental heads' represent the measured groundwater heads in the boreholes taking density variations into account and show the potential for flow in a vertical direction only. 'Freshwater heads' represent the translation of those density (and salinity) variations to an equivalent single density system expressed as head above a common datum. Freshwater heads show the tendency of water to flow horizontally. Head contours and values are shown on COR/517, v.3, figs.4.2-4.6 & 4.8-4.10, but I consider that the diagrams simplify the picture compared with actual conditions in the ground: the relatively smooth contours represent interpretation between quite widely spaced boreholes, and where holes are much closer, as between pairs in the PRZ, the contours become more irregular.

C.41 The freshwater head contours on ibid., fig.4.3, show a very slight tendency for flow inland at depth in the Irish Sea brine zone, otherwise there is a marked tendency for horizontal flow towards the coast in the fresh and saline waters of the Coastal Plain and Hills & Basement regimes. Nirex suggests that the pattern of head gradients towards the coast is topographically related and consistent regardless of the stratigraphy but some features suggest there could be some confining effect of dipping strata of varying permeability. There is no disagreement that there are relatively rapid groundwater flows in the Sherwood Sandstones, especially the upper 150-200 metres, based on the head data, water chemistry, observed discharges, and aquifer pumping tests. It is the flow in the deeper rocks, particularly the BVG, that is most disputed.

C.42 Environmental head contours on COR/517, v.3, fig.4.4, show a general upward component of gradient in the Hills & Basement and Coastal Plain waters, though downward at shallower depths inland of the PRZ. In plan view Nirex interprets this transition between downward and upward head gradients as occurring below the northeastern edge of the PRZ [ibid., fig.4.10].

C.43 Nirex claims it is now possible, from monitoring environmental heads in six of its boreholes in the vicinity of the RCF, to recognise a three-layer groundwater pattern with depth [summarised in NRX/14/12, fig. 6.8]: (i) an upward though predominantly coastward flow of freshwater in the upper 150-200 metres of the SSG in and west of the PRZ; (ii) a zone in the upper 400m or so of the BVG and variably up to the top of the Brockram or into the lower part of the SSG with little or no vertical gradient; (iii) a deeper zone in the BVG, perhaps below 750-900 metres bOD in the PRZ, with upward environmental head gradients. I am not convinced that the pattern is as simple as this. Although some of the local variations in environmental pressure measurements made soon after drilling have become more subdued with time, nevertheless there are still clear irregularities in the vertical pattern in, for example, holes 2, 4 and 5, and contrasts between trends and values at similar depths in nearby holes, eg between PRZ3 & hole 5, or between RCF2 (which shows a slight general downward head gradient in the BVG) & RCM1/RCM2 (with a slight upward trend). [Compare top right diagrams on drgs 010111-010131, COR/518A.] There is no disagreement that there is poor match between the observed environmental heads and what has been calculated in Nirex modelling using base case parameters. It is true, as Nirex stresses, that head differences do not indicate actual flow, but it would be surprising if there were none.

C.44 The Sellafield district and wider Lake District margin are extensively faulted. Faults may have little influence on groundwater flows, or may act as barriers, or conversely as zones of enhanced flow. Nirex has assumed in its numerical modelling that the major faults are flowing features. On the head diagrams in COR/517, v.3, the faults are mostly interpreted as having no influence on the head contours but the two faults just left (NW) of BH11A on figures 4.5 & 4.6 are shown as acting as a significant barrier in the deeper rocks. Although I know that geophysical data give some assistance, it seems to me that there is a considerable amount of speculation in such diagrams. At present I believe there are insufficient boreholes well enough located in relation to the faults for much to be known about head (or density or water chemistry) differences, small or large, across any of the faults.

C.45 As seen in plan view over the Site area, Greenpeace considers that groundwater flow from the fells converges on the PRZ, showing that the PRZ is positioned directly on the main subsurface axis of potential flow from the Lake District towards the coast. However, on a broad scale and in the sandstones at least, the data support the Nirex view that the flow off the hills tends to diverge in response to the topography: north of the PRZ it is predominantly westward and south of the PRZ is more southwesterly [eg COR/517, v.3, fig.4.8]. Modelling by Nirex [ibid., fig.6.2] and by HMIP [GNP/3/16, p.57 last para.] matches this pattern. Greenpeace also says that due to control of these subsurface flow paths by fault blocks, any increased regional flows during future glaciations can be expected to take identical pathways. I would not agree that this argument follows and consider it most unlikely.

C.46 The presence of the wedge of dense Irish Sea Basin brine under the coastal plain means that the main flows in the sandstones will be forced upward to discharge near the present coastline, and that any coastward flows in the BVG basement rocks will also have an upward component. Groundwater modelling should be able to match the location of groundwater discharges. The simple two dimensional picture on a NE-SW section through the PRZ suggests the predominant discharge from the sandstones and Quaternary deposits is very close to the coast and a short distance offshore. Indeed Nirex has demonstrated freshwater spring discharges on the foreshore by sampling and remote sensing, and considers that the 300-400m thickness of fresh and brackish water in boreholes 3 and 13A close to the shore implies that a fair proportion of the fresher waters moving in the upper part of the sandstones discharges offshore. A detailed hydrogeological investigation by BGS (formerly IGS) in the vicinity of Sellafield Works [CCC/4/3] also showed that beach groundwater appeared to be welling up directly from the Triassic sandstones or possibly the base of the glacial deposits. However this same study estimated that rather less than half the water entering the sandstones discharges along the 10.5 km front to the sea, the majority contributing to the base-flows of surface streams. Nirex's own modelling predicts substantial discharges from the sandstones directly into watercourses and shallow glacial deposits along the valleys well inland [COR/517, v.3, fig.6.3]. I am of the opinion that insufficient is yet known about just where the fresher groundwater is discharging.

C.47 Groundwater salinity and density: The relatively simple picture presented by Nirex that there are three main groundwater regimes each with distinct hydrochemical signatures, and that all the gross water compositions can be explained by mixing of the three end members [COR/602, Fig.8], appears to be a reasonable interpretation. However groundwater in the PRZ basement rocks is thought to be a mixture of all three groundwater types - basinal brine (a little), basement saline groundwater, and fresh water [COR/602, p.5 middle para. & Fig.4] - a general indication of the dynamic changes that will have affected the groundwater regimes over geological time and highlighting the potential repository's location close to the junction between the three regimes.

C.48 The Saline Transition Zone (STZ) in the Sellafield area represents the boundary between the fresh waters of the Coastal Plain Regime present in the shallower strata and the deeper saline waters of the Hills & Basement Regime inland or the Irish Sea Regime brines present below the sea and at depth below the coastal plain. A sharp transition might imply little mixing between saline and fresh water whereas a more gradual change might indicate upward flow of saline waters from the BVG into the overlying sandstones.

C.49 The PRZ is located in the Hills & Basement zone so the nature of the contact between the freshwater and the saline waters in that area is of most interest. Partly for convenience of graphical presentation, Nirex takes the STZ to be the depth range over which electrical conductivity of the groundwater changes from less than 10 to over 17 milliSiemens/cm (at 20EC) [COR/525, para.3.2], approximately equivalent to 3.5-6 g/l chloride [ibid., para.3.5] or say 5-10 mg/l dissolved solids. However this corresponds to only part of the range represented by brackish water and certainly not the full range from fresh water to saline water or brine [ibid., Glossary p.G2]. [Note that there are typographical errors in the Glossary. 'Brackish' water is defined as having between 1 & 10 g/l total dissolved solids (TDS). The lower table should show 1 g/l TDS = approx. 0.6 g/l Cl = approx. 3 mS/cm conductivity, and 10 g/l TDS = approx. 6 g/l Cl = approx. 17 mS/cm EC. 'Brines', have over 100 g/l TDS and the table should show 100 g/l TDS = approx. 60 g/l Cl = approx. 123 mS/cm.] Typical deep BVG water in the Hills & Basement zone has over 20 g/l (20,000 mg/l) TDS.

C.50 The vertical salinity (chloride) profiles of the PRZ boreholes do indeed show a relatively sharp transition in that locality, though over a vertical distance of 200m or more [summarised on COR/525, Fig.3.1, but better seen on the individual profiles in Appendix C]. Water density also reflects its salinity. The logs of groundwater monitoring in boreholes [COR/518A] show the density profile for each hole. These are somewhat diagrammatic but all holes in the PRZ display a rapid jump in density over a vertical distance of less than 100-200m [eg Holes 2 & RCF1, ibid. drgs 010111 & 010123] whereas nearby holes 7, 11A and 12A show a transition (indicative of mixing) over a vertical distance of 500-600m [drgs 010114, -119 & -120].

C.51 Inland of the Irish Sea Basin brines the pattern is not as simple as a freshwater (Coastal Plain) regime confined to the sedimentary cover and a saline (Hills & Basement) regime in the BVG. Holes RCF1 & RCF2 in the PRZ and Hole 11A south of the Seascale Fault Zone show high salinities in the lower part of the SSG, suggestive of at least local upward flow of saline water from the BVG. In each hole the chloride concentration in the Brockram is about 10,000 mg/l, reducing upward in the sandstones, in the case of Hole 11A over a vertical interval of perhaps 500m [see COR/518, v.2, drgs 010141 & -189, -145 & -193, -146 & -194].

C.52 The evidence suggests that the boundaries between the hydrogeological regimes are not straightforward. A single 2-dimensional WSW-ENE section though the PRZ shows a salinity distribution and location of the STZ corresponding moderately closely to the idealised conceptual model [COR/525 figs.1.1 & 2.2b] but other dip sections [figs.2.2c & d], a strike section [fig.2.2a], and the STZ contour map [fig.2.3] show a more irregular pattern. The margin of the Irish Sea brine mass is not a simple geometric feature roughly parallel to the coast but is sinuous and irregular, and the vertical distance over which there is a transition from fresh water in the SSG to full salinity groundwater in the BVG in the Hills & Basement zone is up to 200m or more. It is therefore not surprising that modelling discloses differences between calculated and observed salinities [COR/522, v.3, s.7.2].

C.53 It seems to me that the 3-D pattern of salinity distribution over the full Site area is not well constrained. There are insufficient boreholes away from the PRZ, especially to define the sloping front of the brine mass and the zone where fresh waters rise over it to emerge in the vicinity of the present coastline. However general experience suggests the probability that with data from more boreholes the irregularity of pattern will be confirmed and accentuated.

C.54 Groundwater Eh, pH & ionic strength: There is disagreement between Greenpeace and Nirex as to whether the groundwater in the BVG in and around the PRZ is oxidising or reducing, i.e. what is its Eh or redox potential. Greenpeace believes the former, Nirex the latter. Eh affects the speciation (i.e. oxidation state and compounds formed), and hence the solubility and sorption behaviour of redox-sensitive elements in aqueous systems. Nirex anticipates that corrosion of iron and steel will produce a reducing environment in the repository and thereby significantly lower the solubilities of several key radionuclides, including uranium and plutonium. [NRX/15/10, p.iii. 1st para.; p.1 2nd para.; & s.2.1]. It believes the iron/uranium buffering system will remain effective for up to 7 million years at present estimates of groundwater throughflow [ibid., s.4.4], even under a wide range of redox potentials of inflowing groundwater [ibid., p.19], but with numerous assumptions including uniform distribution of materials and solutes along vaults and uniform throughflow [ibid., s.4.4 & 4.5]. Greenpeace believes inflowing oxidising groundwater will have more effect, and will become more important after the buffering influence of the vault containers and backfill wanes.

C.55 It is accepted that measurement of in situ Eh is extremely difficult. Limited determinations on borehole samples suggest oxidising groundwater conditions in the sedimentary rocks, and only slightly oxidising to mildly reducing in the BVG. The alternative approach is to estimate Eh from computer simulations of the equilibrium between the various ions present in a groundwater sample. Nirex uses what I regard as the conventional methodology. It calculates Eh on the basis of equilibrium between ionic pairs, eg sulphate/hydrogen sulphide and sulphate/iron sulphide (pyrite), to arrive at a distinctly reducing figure (Eh about -250 millivolts) for BVG groundwater [COR/525, p.33]. Greenpeace, though, has calculated for a simulated mix of ions with decoupled ion pairs to arrive at the conclusion that the PRZ groundwater may be oxidising. However both parties believe the concentrations of elements in the groundwater could be in general chemical equilibrium with the minerals lining the BVG fracture surfaces. The evidence for the latter conclusion does not seem strong, and I note that BGS, who carried out detailed thermodynamic modelling for Nirex to assess whether water samples from Borehole 2 are in equilibrium with their host rocks, concluded that the groundwater in the vicinity of the BVG of the PRZ is apparently not fully in equilibrium although it may be partially so [CCC/4/7, Summary, 2nd page].

C.56 Greenpeace considers that the fracture mineralogy supports its argument for oxidising conditions: Nirex assumes that pyrite (iron sulphide, FeS_2) buffers the groundwater to a reducing Eh but this mineral is rarely mentioned in borehole logs or is present only as a secondary mineral whereas the iron oxide haematite (Fe_2O_3), generally indicative of an oxidising Eh, is more pervasive. Greenpeace has inspected the Nirex borehole logs and plotted in diagrammatic form where material amounts of pyrite are recorded on fracture surfaces [GNP/3/28, Fig 3.8]. There does appear to be a distinct pattern, with pyrite generally present at depth below a 'redox transition line', but largely absent above. The transition is within the BVG and everywhere deeper than the preferred RCF or DWR, but becomes increasingly deep westward. Greenpeace says this implies oxidising groundwater at shallower depths, in which pyrite would be geochemically unstable, and more reducing conditions below, in which pyrite is stable, although it accepts that the line cannot be precisely defined because metastable iron compounds can survive in slightly 'wrong' redox conditions. Nirex points out that haematite can persist in somewhat reducing conditions, particularly at higher pHs, and that pure pyrite is less likely to survive in oxidising conditions [NRX/15/43, fig.7.1] but a more detailed review paper satisfies me that, although the mechanism is uncertain, iron sulphides have a relatively wide persistency field in oxidising conditions [GNP/3/21, fig.11 & text p.3145 & 3146 first sentence].

C.57 Although the mineral pattern described by Greenpeace does indeed appear real, it might be a reflection of geochemical history rather than present day conditions. It does not for example appear to bear any particular similarity to the distribution of salinity or supposed groundwater flow patterns. The pattern may possibly have been imposed millions of years ago: alternatively it might support FOE's contention that there could be significant changes in fluid flow over say 10^5 years and that zoned calcite crystals found in the BVG indicate (more frequent) changes in the groundwater redox state over time. I believe the conclusion reached by the BGS in 1994 is still valid, that current groundwater Eh, together with in situ pH, temperature and groundwater composition, is uncertain [CCC/4/7, last 2 paras].

C.58 I consider that an adequate working knowledge of redox conditions, pH and ionic composition of groundwater is to be expected as part of the requisite generic understanding of the PRZ and the Site. The RCF should of course provide more information relating to such matters, but I doubt whether Nirex's current understanding of the geochemistry of the groundwater of the Site is yet fit for the purpose of predicting the geochemical effects of RCF perturbation. As for the proposed repository, the current Nirex assessment is that groundwater chemistry will have a secondary role in the evolution of the near field and escape of radionuclides because of the overwhelming and prolonged effect of the chemical barrier but I believe there is much more work to be done, for example on the effects of inhomogeneities in the near field [eg COR/529, s.5.2.2], before it can be said with confidence that the chemistry of inflowing BVG groundwater is of little significance. Eh, pH and ionic concentrations could also matter in the far field, and may be particularly relevant to deeper pathways [see C.115]. Nirex claims that ionic strength of groundwater is not a major factor in geochemical calculations because, in considering a typical flow pathline from repository to offshore discharge location for the Nirex 95 base case, the maximum ionic strength is actually in the vicinity of the repository and declines downstream [NRX/15/30]. However this seems to me to ignore dispersion and diffusion away from the notional pathline [compare say COR/522, v.3, figs.2.7 & 2.11] and variant cases in which flowpaths may be deeper or longer [compare say ibid. figs.2.7 & 7.19].

C.59 Palaeohydrogeology: An important area of geochemical research, and one that could have great implications for a repository safety case, has been the measurement of various solutes in the groundwater that may be indicators of the residence time or 'age' of the water. A short residence time is likely to indicate a fast rate of flow through the system, a long residence time a slower rate. All the significant available methods have been applied: measurement of stable isotopes (oxygen and hydrogen), noble gases, carbon-14, chlorine-36 and helium-4. Parallel work has attempted to date some of the solid minerals that line flowing fractures.

C.60 The deep groundwaters in the PRZ, corrected for drilling fluid contamination, appear to contain no significant tritium (hydrogen isotope ^3H) and therefore cannot contain any modern (post 1953) water [NRX/17/1, 5.4]. Similarly the least contaminated PRZ basement samples appear to contain no Carbon-14 (^{14}C) [ibid., 5.5], pointing to a period of over 30,000 years since recharge.

C.61 However there is divergence of view over the interpretation of stable isotope and noble gas ratios. These are likely to reflect the temperature of precipitation at the time the water entered the ground. The deuterium (^{2}H) and heavy oxygen (^{18}O) isotope ratios for groundwater in the deep BVG of the PRZ and lower part of the Permo-Triassic sandstones west of the PRZ are lighter than present day rainfall and lighter than water in the overlying sandstones and therefore reflect a lower recharge temperature. Nirex ascribes this to the colder climatic conditions that prevailed during the Pleistocene whereas Cumbria considers the differences can be simply explained by different altitudes of the respective recharge areas. I would say that the evidence tends to point in the Nirex direction: altitude differences would not easily explain the different ratios recognised in different parts of the Triassic sandstones; the catchment area likely to have recharged the Sellafield BVG has an average elevation distinctly less than 600m higher than the Sellafield coastal area; and there is good evidence elsewhere in Britain from isotope studies of recharge of Triassic sandstone aquifers associated with the last glacial maximum advance [NRX/17/1, para.5.9]. Similar arguments apply to noble gas ratios which may also reflect climatic and/or altitude effects.

C.62 Uncertainties also exist over the measurement and interpretation of Chlorine-36 (^{36}Cl) and Helium-4 (^{4}He) abundances. Although $^{36}Cl/Cl$ ratios and ^{4}He abundance in BVG water in Borehole 2 suggest a residence time in excess of 1.3 million years, and ^{4}He data suggest similarly old water in Hole 12, results from other holes suggest significantly shorter residence times. There is no dispute as to the difficulties and uncertainties in making the calculations but I agree with Cumbria that no simple and consistent overall picture has emerged.

C.63 I note that the majority of samples analysed for groundwater residence indicators are taken from well testing in the boreholes and, from the evidence presented, I accept that in the BVG these samples will be dominated by flow from the fracture system with relatively insignificant contribution from the pore volume. Thus the apparent water residence times, insofar as they can be relied on, are likely to be fairly indicative of water contained in joints and fractures. The pore waters cannot be younger, but could be older.

C.64 There is no doubt that different explanations are possible for the isotope and noble gas data if the parameters are considered one by one, and the picture is by no means as clear as suggested by Nirex. Nevertheless there are a number of indicators that each point in the same direction and are strongly suggestive of long residence time for the BVG groundwater in the Hills & Basement regime. The case is a long way from being proved and many more determinations are needed over a wider territory but if the data continue to be consistent with a long residence time then that would be a strong factor in assessing regional groundwater flow rates.

C.65 I consider the case is not proven but if the meteoric recharge component of the saline Hills & Basement groundwater can be shown to date from over 10,000 years ago and to reflect climatic conditions during the Pleistocene then there must be a distinct possibility that a similar flushing out of existing groundwaters and recharging with new could take place during the next glacial cycle(s), which could come within a few tens of thousands of years [eg COR/527 p23].

C.66 Specific groundwater impacts of the RCF: No document was submitted to the inquiry by Nirex that quantifies the anticipated impact of the proposed RCF on baseline hydrogeological conditions nor on the long-term repository safety case. Nirex Report 560 (1994) was introduced by FOE [FOE/5/19] and is concerned with these issues but can be regarded as a preliminary scoping study, and is described as such by Nirex. Although no detailed assessment of the direct or indirect effects of the RCF on the groundwater has been presented, this is partly a circular matter because a prime purpose of the RCF is to observe drawdown caused by shaft sinking as a means of validating water flow models, by comparing the effects against predictions not yet made.

C.67 Report 560 is criticised by FOE for using so many modelling approaches that it was difficult for the authors to develop definitive overall conclusions, but I would say it was reasonable at that preliminary stage. Numerous methods were indeed applied in making groundwater inflow and drawdown estimates, including simple porous medium models for flow to a RCF shaft and gallery; a simple resistance model of flow into a gallery from overlying aquifers via a single or interconnected zones of locally enhanced conductivity (ZLECs); a simple 1-D model to estimate vertical flow in the damaged zone behind the shaft lining during the RCF operational phase; a NAPSAC fracture network model of shaft and gallery inflows through zones of enhanced conductivity; and a coarse NAMMU 3-D porous medium model to examine the effects of the shafts on regional heads and flows.

C.68 The report's calculations, making use of much elicited, inferred and judged parameters [ibid s.A3.2 & Table A7], were made for an earlier though similar RCF design than that now proposed: in particular the galleries were of rather smaller cross section and less extensive. It was assumed that the shafts would be fully lined through the superficial strata and sandstones but no other steps taken to restrict water inflow. Seepage of water into the shafts, almost all from the BVG, was estimated of the order of tens to something over $100m^3$/day depending on frequency of intersections with ZLECs [ibid., pp25/26 & table 2.14] and seepage into the galleries of the RCF, on a supposedly pessimistic calculation, of the order of $100m^3$/day, with a slight possibility that it could be into the low thousands [ibid., p.76 & table 2.6]. Heads in the BVG were predicted to fall by over 400m adjacent to the open shaft and some reduction in heads was estimated in the BVG for at least 1km radius around the shafts. Clearly such changes would be significant: a head reduction of this magnitude maintained over a period of years (during the operation of the RCF) would draw in groundwater from a distance and probably would draw in water of different geochemistry from that now present in the immediate locality. It would certainly alter the baseline conditions.
C.69 The indirect effects of the RCF arise because of its proximity or even, as assumed in Nirex Report 560 [ibid.], its physical interconnection with the potential DWR. The report notes that flow through the sealed shafts, roadways and drifts could cause higher groundwater fluxes through the repository vaults and shorter travel times between the repository and the biosphere. It also estimated that several ZLECs will intersect the RCF, and calculated a 1 in 10 probability of a ZLEC connection between the RCF and the Brockram or equivalent. The report actually made fracture network calculations for groundwater flow through an explicit representation of a waste repository that included the RCF and its shafts [ibid., p.A.12, last para.] using a methodology similar to that subsequently adopted in Nirex 95. Figures for flux, travel time and dispersion length were fed into MASCOT radionuclide transport model calculations. Calculations for the modelled cases showed, inter alia, that variations in the permeability of shaft and drift backfill could dramatically alter the time of peak annual risk from radionuclides reaching the biosphere [ibid., p.64, table 3.1]. It would be fair to infer from the preliminary calculations in this report that by introducing additional hydraulic conductivity into the hydrogeological regime the RCF could potentially damage the repository safety case.

Potential of the Natural Geosphere Barrier

C.70 The extent to which the rocks of the geosphere may retard or arrest radionuclide transport from the repository depends on numerous factors including the overall geological structure and stratigraphy; the effective permeability of the rocks, which depends on the porosity or fracture pattern and connectivity; water flow paths and travel times, which reflect the foregoing as well as topography, recharge and discharge and are arrived at principally by modelling; and geochemical and hydrochemical interactions, including sorption processes. These aspects are considered below.

C.71 Geological structure & stratigraphy: Nirex claims that the geological structure and locations of faults are now robustly defined, but the maps and sections of the PRZ presented at the inquiry are largely new interpretations, significantly revised from relatively recent previous versions, eg compare the interpreted fault pattern and structure contours across the PRZ on drawings 010053 & 010054 [COR/518, v.1], the former being the same as at December 1993 in COR/517, v.2, the latter dated June 1995.

C.72 As discussed earlier, groundwater heads and flows and the hydrochemical regimes are best understood in a general NE-SW zone through the PRZ and relatively well in a NW-SE direction, reflecting the pattern of deep drillholes, but I consider that the bedrock geology is rather better known in 3 dimensions, at least at the coarse scale, because of the greater coverage of geophysical surveys of various types, and at a rather finer scale in the vicinity of the RCF shafts because of closer boreholes and more seismic tomography.

C.73 Deep drillholes can make few intersections with steeply dipping faults and provide little information on their frequency and orientation so the picture of fault locations has been derived predominantly from interpretation of seismic surveys, but the BVG rocks are more difficult to characterise seismically than the overlying layered sedimentary strata because they have relatively few reflective surfaces.

C.74 The variability of throw, pattern and characteristics of the faults has already been mentioned [at paras. B.96-99 above], but an impression of the distribution and variability of the faulting in just a small area of the PRZ can be obtained by comparing structure contour maps for three horizons in the BVG, namely COR/530, drg.010054 with figs. 3.4 & 3.5. (Note the slightly larger scale of the latter.)

C.75 I am struck by the example given by FOE of how difficult it is to identify fault F2, probably the most significant fault traversing the PRZ, even in seismic tomograms. This fault, together with F1, F3 and F202, is a main structural controlling feature of large throw and claimed to be robustly defined. F2 is said to be identified on the tomogram BH5-RCF3 [COR/530 para.3.4] but Nirex advances a number of distinctly different alternative interpretations of the geology between the two holes [COR/513 figs 10-13]. The preferred version [ibid. fig. 14] shows feature 'A'(= fault F2) cutting borehole RCF3 at 605 metres below rotary table (mbRT) whereas the summary log of RCF3 [COR/518, v.1, drg. 010147] shows fault F2 as several strands between about 525 and 600 mbRT, and a different fault, F201, intersecting at 605m depth. This coincides with the interpretation elsewhere, which suggests the shallowest of the strands is the main F2 fault plane [COR/524, fig.3.1]. The 'fault' is clearly a complicated structure.

C.76 By choosing a potential repository location in volcanic rocks, and specifically the Borrowdale Volcanics, Nirex has created greater difficulties and work for itself than seems likely in some other potential types of host rocks. The mode of formation of the BVG, with its ash falls, lava flows, reworked deposits and intruded sills and dykes, makes it inherently variable, but the additional effects of faulting, slumping and deformation caused by caldera collapse add to the complexity. The evidence is strongly in favour of FOE's contention that the BVG of the Sellafield district was the product of and disturbed by a Lake District-wide piecemeal caldera. BGS research for Nirex [FOE/2/3, Summary & s.4] describes in some detail how the thick volcanic sequence of the Sellafield district may best be interpreted as the infill of a caldera system or systems, and [ibid., s.4.1] how rapid lateral variations in thickness, abrupt facies changes and steeply inclined contacts are consistent with volcanotectonic faulting. FOE/2/2, fig.17 illustrates in diagrammatic form the complicated sequence of events, with volcanic eruptions, the activation and reactivation of faults, etc.

C.77 Whilst the BGS has been able to establish a broad stratigraphy based on average whole-rock chemical composition which can be correlated around the PRZ and perhaps eastward for some kilometres, it has not been able to correlate the stratigraphy west and northwestward from the PRZ as far as boreholes 3, 7A and 14A [FOE/2/3, p.27 2nd para. & section 2]. More importantly, there is no doubt that there are very great vertical and horizontal lithological variations over distances of only tens of metres [eg COR/530, fig.2.2]. Indeed COR/524, para.5.1 says just that, but in respect of both the BVG and Permo-Triassic rocks in the vicinity of the RCF south shaft. The Permo-Trias of West Cumbria did have a more varied depositional history than most comparable strata elsewhere in Britain, being much influenced by proximity to the Lake District massif [see diagrams COR/517, v.1, figs.5.4], but I would still not equate the lateral variability of the SSG with that of the Borrowdale Volcanics.

C.78 The difficulty of correlation over even short distances in the BVG is well demonstrated by the need to consider alternative and preferred models for the local geology [ibid., fig.5.1] and by the supposed repetition of the Longlands Farm Member at the base of RCF2 [COR/530, fig.2.2], accepted as caused by a volcanotectonic fault [ibid., para.3.14, which cites FOE/2/2]. Nirex says these problems relate to just one small part of the site and that there is no difficulty in correlating elsewhere, but this is the part of the site that has been explored in most detail and the evidence suggests to me that any similarly sized volume of BVG elsewhere in the PRZ or beyond will be just as variable.

C.79 I accept too the FOE evidence that the BVG, particularly the ignimbrites, would be expected to exhibit cooling-contraction joints but whose distribution and style are likely to be very unpredictable. Ignimbrites predominate in the PRZ rocks but the Nirex reports do not appear to recognise cooling-contraction jointing.

C.80 The Nirex 95 modelling simply divided the volcanic rocks in the vicinity of the site into those within 400m of the top surface of the BVG and those deeper. Nirex understates the stratigraphic complexities of the BVG and the difficulties of expressing the variations in 3 dimensions yet accepts there are general relationships between the main stratigraphic divisions (the named members and formations) and the hydrogeological properties of the rocks, the rock quality, structural domains and fracture frequency. I consider that those stratigraphical variations are very relevant to RCF and DWR siting, design and modelling, they are a long way from being resolved, and for these purposes Nirex will need to develop a much better understanding of the 3 dimensional geology over a wider area than at present.

C.81 <u>Flow characteristics and conductivity of the rocks</u>: Nirex has carried out an appropriately wide range of in situ hydrogeological testing and monitoring within the constraints of a borehole-based investigation, in an attempt to develop an understanding of the flow characteristics and conductivity of the rocks, in particular the associations between flow and discontinuities in the BVG and the degree of hydraulic connection between the basement rocks and sedimentary cover. The work has included full sector tests and environmental pressure measurements over long sections of borehole, and fracture network tests, discrete extraction tests and short interval hydraulic tests at progressively smaller borehole lengths [eg COR/524, s.7.6], with monitoring to see what effects if any are caused in surrounding holes. Additional cross-hole hydraulic testing and a Borehole RCF3 Pump Test have been carried out.

C.82 The environmental heads in Boreholes 2, 4 and 5 each showed a downward gradient in the BVG between about 600 or 700m and 800m bOD, associated with a fault or fracture zone. The heads at depth were very similar to those in the shallow Sherwood Sandstones, implying that there may be a direct hydraulic connection between the two. [See environmental head graphs on COR/518A, drgs. 010111, -112 & -113.] This has important implications for the safety case and modelling of the groundwater flow system and was remarked on in RWMAC's 13th & 14th annual reports [GOV/405, para.4.20 & GOV/406, para.3.27]. Nirex was sufficiently concerned that it sank two extra holes (PRZ1 to investigate BH2 effects and PRZ3 to investigate BH5) and carried out BH2-BH4 cross-hole hydraulic testing. The cross-hole testing, between boreholes 120m apart, produced extremely small responses in Hole 4 to pumping in Hole 2 and no obvious association with faults between the two [NRX/14/12, fig.6.6]. However Hole PRZ3 confirmed an environmental head pattern similar to Hole 5, and RCF2 also showed a slight downward gradient in the BVG [COR/518A, drgs.010129 & -124].

C.83 Other cross-hole hydraulic responses suggest definite connections between the basal 75m or so of the SSG (the North Head Member), the Brockram and the BVG [COR/524, para.7.29] though none of the monitoring and testing has shown clear connections between the main body of the sandstones and the BVG.

C.84 The RCF3 Pump Test, in which water was pumped in turn from test lengths of the borehole in the St Bees Sandstone, Brockram and BVG for periods of days to months and then allowed to recover whilst pressure gauges were monitored in that and other boreholes, ought to be a better guide than other, shorter duration types of test. [See COR/518A for graphs of monitored heads; NRX/14/12, fig.4.3 for borehole locations; and ibid. fig.6.7 for a more clearly annotated copy of the hole RCF3 data.] I have some reservations about the shortness of the drawdown periods, particularly of the Brockram Test, because heads were still falling in some of the gauges when pumping was stopped, and similarly about the recovery periods when some heads were still rising at the time the next period of pumping started. Nevertheless the results do appear to support the provisional Nirex conclusion that in the central part of the PRZ at least there is little connection between the BVG and the overlying sandstones.

C.85 In Hole RCF3 itself pumping caused a response only in gauges in or a little above the pumped section (in the Brockram test, gauges P9 & P10; in the sandstone only P11 & P13; and in the BVG gauges P3 & P4 and to a lesser extent P5 & P6 above). Similar responses were observed in nearby boreholes in the monitoring network: BVG pumping in RCF3 appears to have affected only the BVG in the neighbouring RCF and RCM holes, and the Brockram test appears to have produced a response only in the Brockram and upper BVG in the same boreholes plus Boonwood. The sandstone tests caused responses more widely, with small effects in hole 5 to the west and the group of holes 2, 4 & PRZ2 to the south. In most cases drawdown was confined to the sandstones and perhaps slightly in the Brockram. Curiously though the graphs suggest to me that the RCF3 sandstone pumping tests produced a slight response in the BVG in Holes 2 and 4 some 500m away.

C.86 The Nirex evidence that the RCF3 sandstone test was conducted just above the Saline Transition Zone but the pumped water remained fresh throughout, and that the Brockram test was conducted immediately below the STZ and the pumped water remained saline also support the principle of little vertical connectivity in the vicinity of RCF3, although again I have some reservations over the duration of the periods of pumping.

C.87 The degree of heterogeneity of environmental heads within individual boreholes is, as Nirex says, a characteristic of fractured rock masses and does suggest that connectivity cannot be too great. Nevertheless the broader patterns of environmental head gradient in some of the boreholes could suggest local fairly direct hydraulic connections between the BVG basement and overlying sandstones. This possibility has not yet been adequately confirmed or discounted. Similar testing in more boreholes would go some way towards resolving the matter but the much greater scale and duration of constructing the RCF shafts and galleries would be a powerful indicator of the nature and extent of any connections.

C.88 As for identifying and characterising the flow zones, the general nature of flow in the sedimentary cover appears to be quite well established: largely matrix flow with some contribution from bedding plane fractures in the Sherwood Sandstones and a combination of matrix flow and fracture flow in the Brockram. In the BVG, flow is undoubtedly principally through fractures but has been demonstrated to occur through only a small proportion. No direct and consistent association has been found between flow zones and any single geological characteristic, leading Nirex to conclude that partial correlations exist between many factors [COR/523, paras.7.2 & 7.10].

C.89 The current assessment of those partial correlations is summarised in COR/523, section 6 and appears plausible, although the supposed associations with mineralisation episodes is a level of detail that is not easy to assess simply from summary documents. The strong relationship with the latest (ME9) phase of mineralisation is not unexpected but does not of itself directly indicate the age of the flowing fractures. More important could be the association with the ME6 phase of mineralisation, which would suggest that many of the fractures carrying flow today are essentially the same as those formed as long ago as 200 million years. The finding that 20% of the BVG flow zones occur within fault rock and 47% within 5 metres of a fault might be thought as a good reason why considerably more information is required on the locations and characteristics of the fault systems of the locality [see COR/523, ss.4.18 & 4.19].

C.90 Nirex claims that the hydraulic conductivity of flow zones in the RCF South Shaft area shows an apparent 'linear' decrease with depth, but the plotted test results [at upper left on all COR/518A drawings] show much more variable values, though generally higher in the top say 200m of the volcanics. In any event the frequency of flow zones is variable and shows some association with particular stratigraphical divisions, notably more at intervals in the Longlands Farm Member and at a level in the Sides Farm Member, but generally absent in the Town End Farm Member.

C.91 Sorption studies: Sorption of radionuclides in the geosphere is potentially important in determining post-closure performance of a deep repository although Nirex says its work is not crucially dependent on sorption since dilution and spreading will also be effective controls. Sorption processes are those chemical and electrostatic interactions by which substances, in this case radionuclides, dissolved in the groundwater (or perhaps carried along as colloids or gas) become temporarily or permanently transferred to the rock or soil. There are numerous sorption mechanisms [see COR/529, p24 Box 11] and many variables. Sorption coefficient (K_d) values are needed in performance modelling but are different for the various radioelements and may vary with pH, ionic strength, temperature, available surface sites, and concentrations of the sorbing element and competing sorbing species [COR/529, p.25 Box 12]. For particularly unreactive radioelements such as chlorine and iodine, sorption is not as relevant as groundwater travel time.

C.92 Thus sorption behaviour is recognised as being very complicated. A starting point is a knowledge and understanding of the chemistry of the groundwater, the solubility and reactivity of radionuclides, and of the relevant mineral surface chemistry.

C.93 The overall composition and patterns of groundwater are now relatively well understood but there remain uncertainties over local variations (representing the degree of mixing of waters from different regimes) and the important factors of Eh and pH which will not only influence sorption in the geosphere and biosphere but also (long term) repository reactions. Similarly there are uncertainties over solubilities and thermodynamic data for individual radionuclides, especially in the somewhat extreme conditions of the repository near-field and near-geosphere but also in the low ionic concentrations of general groundwater in the host rocks; the extent to which organic degradation products will affect solubility and compete with sorption; colloid populations, radionuclide/colloid associations and the potential for colloid transport through pores and fractures in different rock types.

C.94 Sorption and sorption processes are extremely difficult to measure in the field because of practical difficulties of sampling and the changes that occur whilst samples are being returned to the laboratory though techniques are being developed [GOV/630, pp.200-203]. The majority of the work has therefore been laboratory based, but the programme of research has been relatively short for the BVG and other rock types relevant to Sellafield. Reaction experiments with intact rocks, particularly through-diffusion, are extremely slow so 'batch' experiments using crushed rock have been used predominantly [COR/529, pp.28 & 29]. Such experiments themselves take months, but the timescales of all laboratory experimentation are extremely short compared with those of geological processes and the required period of repository safety.

C.95 Reactions on the freshly exposed surfaces of crushed rock used in batch experiments may not be representative of those with the natural, mature surfaces of fractures and pores. Laboratory experiments have been made using materials 'aged' by rapid hydrothermal alteration at elevated temperatures, and whilst they may produce secondary surface minerals similar to centuries of natural weathering [FOE/8/17, Abstract & p.111 top right] it is not certain that they can reproduce natural mineral assemblages and at best such experiments can only inform about ageing processes, as acknowledged by Nirex at the inquiry.

C.96 Such secondary minerals could reduce the ability of the host rocks to sorb radionuclides, but close to the repository excavations the plume of alkaline water could additionally precipitate metastable calcium silicate hydrate minerals in pores and fractures. It is not clear whether, in converting to more stable minerals, their retardation potential will be reduced or whether they may lock in some radionuclides. Similarly the oxygenated conditions of the repository during its active life may lead to the precipitation of iron oxides and hydroxides in the excavation disturbed zone of rocks, with consequent enhanced radionuclide sorption. I do not believe the experimental results are yet clear enough to be confident just how the sorptive capacity of the host rocks, especially of the BVG, will evolve under the effects of the plume of alkaline leachate that it will generate.

C.97 In addition to sorption processes, radionuclide transport may be considerably retarded by diffusion of dissolved radionclides into immobile water in the rock matrix. Experimental work on determining diffusion coefficients and accessible porosity of Sellafield rock types appears to have made good progress in the laboratory but uncertainties remain in scaling up results to represent field behaviour. In situ tracer studies in the RCF would help but again the timescale and extent over which they could be conducted would be small in comparison with geological processes.

C.98 The experimental work by Nirex and equivalent foreign agencies have shown that there is a wide variability in measured sorption coefficients for broad groups of rocks and many unknowns [FOE/8/21 tables A2-A4]. Databases for values of K_d obtained using the isotherm approach are being discarded for values based on thermodynamic modelling [FOE/8/34, pp.86-88,93 & s.5.5.1], however Nirex now favours measured data specific to the relevant Cumbrian rocks for use in PDFs (as with solubility data). At the time of the recent Royal Society report, sorption PDFs for the majority of radionuclides were provided by 'trained expert' and just a few were derived by formal group elicitation [COR/605, p.140]. Thus Nirex 95 modelling used elicited PDFs for sorption based on data from batch experiments obtained over laboratory timescales, with an additional multiplier to allow for organic complexants [COR/522, v.3, s.4.3], so there must be many uncertainties.

<u>Proposed chemical and engineered barriers - properties and interactions</u>

C.99 There has been a considerable programme of research into the performance of steel and to a lesser extent concrete under conditions that might indicate the resistance of waste containers under repository conditions, particularly corrosion rates and mechanisms [COR/529, s.2.2.1]. These are areas where Nirex was able to build on an immense body of knowledge in the fields of metallurgy and concrete technology. I believe there should be good confidence in this aspect of the work.

C.100 The processes by which corrosion and degradation of the waste and its packaging are expected to lead to anaerobic, reducing conditions and the liberation of gases once the vaults become re-saturated appear to be fairly well understood although I note that Nirex is reviewing whether radiolytic reactions (due to irradiation of water) may be more significant than previously thought. Such reactions produce oxidising species and may affect gas generation rates and local Eh which in turn may affect radionuclide solubility and transport. [COR/528, p.12]

C.101 In excavating the DWR it is intended to reduce significant water inflows by pressure grouting of the rocks, and prior to repository closure, high integrity seals will be installed at appropriate locations in access tunnels and shafts (perhaps also at intermediate points in vaults). Thus there is undoubtedly a need for sealing and grouting experiments, but to be meaningful these must be done in the intended host rocks under conditions comparable with that of a DWR. Work in overseas underground research facilities has shown the practical difficulties in carrying out such work, for example sealing experiments in the Canadian URL suffered leakage at the concrete/rock interface [FOE/6/29, p.6] and experimental injection of water into boreholes gave unexpected results [ibid., Figs.12,13; p8 col.1 penult para]. Similarly at Stripa grouting appeared to be fairly ineffective in reducing water inflow [FOE/7/20, p133 last para; p134 last para; p135 penult para; fig 4.44; p197 4th & last paras; p199 middle] although Nirex claims the objective was only to divert flow.

C.102 There is a need for better understanding of the short-term physical and handling characteristics of the NRVB material, including pumpability and methods of placement, excavability, and in situ strength and permeability. Most of this experimentation could be done at the surface or in any other suitable cavity although Nirex is considering trials in the RCF of placement and breaking out.

C.103 The chemical behaviour of NRVB is of crucial importance, how its chemical properties may evolve, how it will condition and control the repository porewater chemistry, and for how long it will retain its buffering effect. Chemical changes may also affect its physical properties, by blocking pores or opening cracks for example. The use of porous cementitious grouts to permit gas to escape and relieve pressure build-up is contemplated at the Swedish Final Repository [NRX/15/9, p.84 middle], and in Switzerland in a LLW/short-lived ILW repository at Wellenberg and the long-lived ILW section of a deep repository [COR/605, s.4.1.2 3rd & penult. paras.] but it is not evident that these grouts are intended also to produce the same chemical buffering effects hoped for with NRVB, and the fact that Nirex has applied for a patent on NRVB is an indication of the novelty of the material. Intensive laboratory work on the chemical containment of radioactive wastes by such a barrier has been and can be done. The maintenance of a high pH over a long period is considered essential but laboratory work can never replicate such a slow evolution of the cementitious backfill. This can only be estimated on the basis of theoretical chemical evolution.

C.104 Nirex has predicted the maximum rise in repository temperature and its subsequent decline. Estimates of the rate of heat dissipation will rely on knowledge of the thermal conductivity under dry then saturated conditions of the grouted backfill and the surrounding rock. It seems to me that this work does not require in situ experimentation and the assessments already have a good foundation. It is appropriate therefore that Nirex has been carrying out a range of laboratory experimentation at temperatures up to at least the maximum anticipated in a repository. Further work recognised as being needed into the effects of elevated temperatures includes the dispersal of gas from accelerated corrosion reactions and the survival and activity of microbes.

C.105 Slow recrystallisation and other ageing processes will affect the ability of the NRVB to retard or immobilise radionuclides but experiments that attempt to accelerate ageing effects require elevated temperatures and produce minerals that may not be created under natural circumstances [COR/528, s.3.2.2(b) & COR/529, p.19]. Laboratory experiments cannot be run long enough to resolve such questions but natural analogue studies such as that at Maqarin in Jordan provide useful pointers.

C.106 The formation of cracks within the backfill and the properties of reaction layers expected to be formed in them by contact with the groundwater are being studied. They could significantly alter the buffering performance of the NRVB and rates of migration of dissolved radionuclides but wide variations in effect have been found between layers of different composition [COR/529, p.19 rt col.].

C.107 The important task is to understand and model the processes by which radionuclides may be carried through or arrested by the chemical barrier. The progress that Nirex is making in obtaining adequate thermodynamic data to model the release of radionuclides by solution into and sorption from near-field pore water is discussed at C.114-116; the process of colloid formation and stability in the cementitious grout and backfill and whether the possible colloid types could affect repository performance at C.117-119 [& COR/528, s.3.2.3]; and how gas may flow through the NRVB and whether gas bubbles can carry radioactive colloidal particles in the following paragraphs [& ibid.].

Gas Generation and Migration

C.108 The cementitious vault backfill (NRVB) has been designed to permit the escape of the substantial volumes of gases that will inevitably be generated by corrosion of containers and degradation and decomposition of the wastes. Research is needed into the physical aspects of gas migration, firstly on how gas enters the water-saturated fracture network to aid prediction of gas pressures and their potential to induce repository or rock fracturing, and secondly into the mechanisms, pathways and travel rates of gas migration through the excavation disturbance zone (EDZ) and geosphere. This would include the potential for coupled gas-water flow and also possible blocking effects on groundwater flow once gases have entered narrow fractures or pores. Such work requires in situ observation and testing although to date appears chiefly to have been confined to mathematical modelling [COR/509, section 3]. Research is also needed into the chemical consequences of gas migration, for example interactions with the host rock or repository backfill, especially if carbon dioxide is not wholly absorbed by the cementitious backfill, and on the ability of gas bubbles to increase the mobility of radionuclides by attracting colloids and other small particles [COR/528, s.3.2.3 p14].

C.109 There appears to be a good understanding of the mechanisms of gas generation and the likely volumes and rates of production and of composition, but greater uncertainty over the physical influence of gas generation on groundwater flows and its chemical influence on near field and geosphere reactions and radionuclide transport. Moreover the simple existence of an air-filled operational repository for several decades (and an RCF) would be expected to have some effect on the surrounding rocks. Nirex says that much of the required information on the possible significance of gas-water interactions on radionuclide transport is now available but it appears to be awaiting peer review and publication.

C.110 Nirex participates in international work on gas migration through rock and its effects [COR/605, 8.2.6], which will certainly assist in the development of modelling, and has been carrying out its own experimental programme at Reskajeage Quarry in Cornwall, but I consider this is an area of research for which there is no substitute for practical in situ experimentation and investigation in the intended host rocks.

Potential Excavation Disturbance from RCF and DWR

C.111 A knowledge of the geotechnical properties of the rocks and superficial strata is important in assessing the ease or difficulty of construction of the shafts and galleries of the RCF and potential repository, and their optimum orientation and layout for stability. I believe Nirex now has a good understanding of the basic mechanical properties of the Sellafield rocks, adequate to make preliminary excavation designs, but there are numerous uncertainties about the likely extent and behaviour of zones of excavation disturbance associated with full size repository vaults, tunnels and shafts at depth. Such uncertainties could only be explored by observing the rocks at close quarters in excavations of the sort planned for the RCF.

C.112 The work on measuring in situ rock stresses by hydrofracture methods, borehole breakout studies and overcoring is relevant not only to the excavation engineering but also to understanding the tectonic history of the locality and the stress regime in relation to earthquake susceptibility and effects. It seems to me that the vertical stresses and directions of maximum horizontal stress are now known with some confidence [NRX/14/13, Table A.13]. The quoted best preliminary estimate of the maximum horizontal stress direction of N165E (approximately NNW-SSE) is consistent with published data for NW England and Western Europe and in my view supports the Nirex perception of the tectonic stress regime as discussed below in the context of seismicity.

C.113 The erratic or unexpected experimental results referred to by FOE from Stripa, the Canadian URL, etc are not really surprising. Whilst there is a wealth of mining and civil engineering experience on mechanical strains caused by excavation, and such effects are usually fairly predictable, there is much less data on the changes induced to groundwater flow and the effects are much more variable. The conclusions of the URL tunnel experiment [FOE/6/29, p.9] are pertinent, that the excavation disturbance zone is very site specific and in the URL depends on the shape and orientation of the excavation, physical characteristics of the rock mass and the stress field. Nevertheless I would say that the effects of stress changes on conductivity typically extend only small distances into the rock behind the tunnel surfaces - as little as 0.26m at the URL [ibid.p.8]. This contrasts with the assumption made by Nirex in repository modelling that excavation disturbance could increase hydraulic conductivity parallel to the excavation walls by up to two orders of magnitude for a distance of up to twice the excavation diameter.

Physical and Chemical Properties of Individual Radionuclides

C.114 Solubility and reactions at high pH: Nirex has been carrying out an extensive programme of experiments into the solubility of numerous radioelements at the high pH values characteristic of the planned repository, but the intended high pH, high free alkalis and low Eh of the engineered repository and anticipated period of raised temperatures lead to areas of complicated chemistry and greatly affect the solubility and reactivity of individual radionuclides, often beyond the range of conditions for which there is much previous research data.

C.115 Discrepancies between predicted solubility and experimental results, and inadequate data on equilibrium relationships at different temperatures and ionic strengths, as asserted in particular by FOE, seem to be borne out by the references cited. However it is true that in performance assessments Nirex does not directly use these chemical models but instead uses laboratory measured data to construct PDFs from which values are sampled: the experimental results are used as inputs supported by chemical equilibrium modelling, not the other way round. It seems to me though that in addition to research on reactions in the highly alkaline environment it is relevant for Nirex to have an understanding of reactions in brine groundwaters because there could be a case for siting the repository deeper and more westward in the BVG. It is also relevant to understand reactions across all the salinity variations in the Hills & Basement groundwater flow regime.

C.116 The body of evidence presented suggests to me, as a geologist, that there is still relative uncertainty over the solubility of many radioelements even at fairly standard conditions of pH, Eh and temperature; that there is yet greater uncertainty in extending the results to more extreme conditions; and that the databases expressing thermodynamic equilibria with major anions are likely to be subject to significant further adjustment. There appears still to be a lack of experimental data over a wide range of conditions relevant to a DWR for numerous radioactive elements.

C.117 Colloids: Research into natural colloids and colloids formed in the waste and cementitious backfill, their behaviour in the near field and geosphere, and the ability of radionuclides to become sorbed and transported by colloids is less well advanced than many other lines of study. There are so many possible colloidal combinations and so many factors, chemical, electrochemical and physical, affecting their stability and mobility but the maintenance of highly alkaline, high ionic strength near field porewater is likely to be important. Nirex appears to be concentrating in the first instance on the generation of cementitious colloids associated with vault backfill and their behaviour in the varying water chemistry of the near field and geosphere boundary [COR/529, s.4.2.3] but has identified broader areas needing to be investigated [ibid., s.4.1.3].

C.118 HMIP said in evidence that oxides or metal particles may be transported as well as colloids though HMIP commissioned research papers [listed in HMP/1/2] deal only with true colloids. The objector Mrs M Higham also expressed great concern about the behaviour of plutonium dioxide particles released from a repository. Although she does not regard PuO_2 as a colloid she maintains it behaves in a similar manner to a stable colloid and therefore can be transported readily through the geosphere with the flow of groundwater. I agree from the evidence of the parties that substantially more research is needed on colloids and other fine particulates, regardless of the precise technical distinction between them.

C.119 Most of the work on colloids is laboratory based and necessarily so in exploring the behaviour of wastes and repository engineering materials. There is a need to understand the presence and behaviour of colloids in the natural geological system but it is difficult to sample groundwater colloids, especially in boreholes at depth, as also experienced in natural analogue studies [GOV/630, p.247 1st para.]. The proposed RCF would afford closer access to the relevant groundwater and I would have expected the chances of obtaining representative samples to be improved, though in evidence Nirex accepted that it may experience the same sampling difficulties in short boreholes from the RCF as in deep holes from the surface.

C.120 Reactions with organic matter: Organic matter in the waste will produce degradation products, some of which have been shown to increase the solubility or reduce the sorption of radionuclides. A significant programme of research has been started, particularly into cellulose degradation and its effects, and into plutonium solubility and complexation with organic compounds [COR/529, s.4.2.1] but it is a wide field and much of the work seems to be novel. It would not be practicable to look at the individual effect of each of the many organic species in the waste leachate so Nirex has been concentrating on what it hopes are key compounds and fractions and expects future research to focus on achieving a better understanding of the underlying mechanisms [ibid. p.76, (iii)]. Research on the influence of organic matter would be necessary regardless of the location of the repository.

Longer Term Geological Processes - Climate and Tectonics

C.121 It is necessary to consider long term natural processes and events that might affect the repository performance, either by direct physical disruption or by changing the geological or hydrogeological characteristics of the geosphere. The principal considerations are tectonic movement, particularly earthquake hazard, and climate change, and their influence on groundwater flow and indirectly on the geochemical environment. The possibility of meteorite damage to a deep repository is calculated to be extremely slight (leaving aside the obvious direct consequences of any sizeable surface impact) and other processes such as volcanism do not appear to be relevant to this corner of Northwest Europe in a timescale of at least some millions of years. Nirex's main approach has been the conventional one of studying past geological and climatic changes and effects as a guide to what might happen in the future.

C.122 Tectonics & seismicity: Research into tectonic activity and risk over geological timescales must consider earth movements on a regional and wider scale but site characterisation studies can assist with the dating of episodes of activity. The evidence for dates is somewhat confusing and contradictory. Greenpeace suggest that the Lake District Boundary Fault zone has been active within the last 60 million years, based on contours of estimated regional uplift but I consider this evidence is weak and I take Nirex's points as to the paucity of data points and limitations of the method of dating using mineral fission tracks. (NB:- the scientific abbreviation Ma = million years is used in some reference documents.)

C.123 The small number of radiometric age determinations on fault rock minerals have given ages well in excess of 100 million years, lending support to the Nirex belief that the last major episode of faulting in West Cumbria occurred over 100 million years ago, but a single sample gave an estimated age of 60 million years. Nirex ascribes this date not to faulting but to an episode of geothermal warming even though it falls within a period around the Cretaceous-Tertiary boundary which Nirex itself recognises was one of regional and wider uplift and which may have been accompanied by active faulting. An age of 100 million years also contrasts with the assessment by HMIP's contractors [GOV/613, p.79] that regional tectonic evidence suggests the most recent phase of compressional and strike-slip deformation may have been in the Oligocene, 40-30 million years Before Present. (Faulting is not explicitly mentioned but significant deformation in this particular district might be expected to result in reactivation of faults.)

C.124 Features that might indicate geologically recent earth movements, such as earthquake-induced faulting or slumping of glacial deposits, are difficult to identify and investigate but there appears to me to be no significant evidence for the existence of neotectonic features onshore in the Sellafield region and the indications offshore are weak and open to alternative explanations.

C.125 Thus although direct methods aimed at dating the most recent period of faulting point to a considerable age - perhaps 60 million years - there remains doubt and it seems to me that the Sellafield site is located in a zone where one might suspect the possibility of more recent tectonic activity: it is located along a major structural boundary between the Irish Sea Basin and the Lake District block; the granite masses under the Lake District represent a gravity 'low' so there may be a tendency for uplift; erosion of the Lakeland fells may induce uplift and sedimentation in the Irish Sea Basin may induce downwarp; and it lies in one of the more seismically active regions of Britain.

C.126 Further research can be done on the dating of faults and the evolution of the fracture systems, for example by studying mineral fission tracks and fluid inclusions, but require sampling of fault and fracture infill materials. The RCF would afford limited access to fault zones.

C.127 There is disagreement as to whether the crustal rocks of the British Isles are in an extensional tectonic regime, or a compressive or strike-slip (shearing) stress regime. The relevance is that if the crust is in tension it is more likely to be subject to active faulting and the possible associated hydrogeological effects noted below. GOV/613, an HMIP report on tectonic hazards for UK nuclear waste repositories, notes that Britain, in contrast to other intraplate regions, is in an extensional regime [p.30, penult.para.] but in a more detailed explanation [sections 3.2.5 & .6] says that borehole breakout measurements and seismic focal mechanism studies suggest that strike-slip and normal fault styles are possible, indeed dominate, over much of Britain and that for the larger faults strike-slip predominates, generally with some extensional component. A Europe-wide review of tectonic stress measurements [NRX/14/6, p.11.790] is consistent in saying that much of western and northern Europe is subject to a strike-slip regime characterised by NW to NNW compression and NE to ENE extension. The Nirex Sellafield in situ stress measurements appear to conform to the same trend (see C.112 above) as does BGS interpretation of a number of modern Cumbrian earthquakes.

C.128 I would say that the evidence favours the Nirex view, but the existence of a local extensional stress pattern in the SW Scottish Highlands [NRX/14/6, fig.2a], in the area of maximum ice load during the Pleistocene, suggests that the Lake District, another area subject to ice loading and now experiencing isostatic rebound, could be similarly affected, either now as a legacy of the last glaciation or in the future. The HMIP report [GOV/613, p.64] notes that the general absence of rebound stress signature in the post-glacial rebound areas suggests that the stresses continue to be released on faults.

C.129 I consider that Nirex has made the maximum effort to obtain data on modern seismicity in the Sellafield region. Information on the occurrence of earthquakes in the region and more local to the Sellafield area has been obtained from historical records, culminating in the publication in 1995 of a four volume report on the seismological database. The historical record of all British earthquakes has been intensively researched and it is likely that little new information will emerge about events over the past few centuries. However a continuous flow of new data is coming from ongoing instrumental monitoring. In addition to the general network of seismographs in Britain and NW Europe the BGS Cumbrian Microseismic Network, inaugurated in 1992, is capable of recording very small events within a radius of about 60km of Sellafield [NRX/14/13, s.A.11]. Such information is useful in identifying the depth, location and characteristics of the focus of seismic events. However the period of instrumental monitoring, whether local or national or beyond, is miniscule in relation to the timescale over which repository safety needs to be assessed. Even so I note that, as one might expect from the structural geological setting, that West Cumbria and the North West generally are among the more seismically active areas of England.

C.130 Hydrological effects induced by seismicity were given much emphasis by Greenpeace. Earthquakes can undoubtedly significantly change the hydrological regime around faults, causing changes in the water table and expulsion of water at the surface over days and sometimes months. The most significant response is found to accompany major normal fault earthquakes. Reverse fault earthquakes show little or no effect, and strike-slip fault movements have variable effect but relatively small [GNP/3/7, Abstract; GOV/613, sections 2.2.4, 2.3.3 & 2.4.1]. There is no international consensus on the precise mechanisms and effects although it seems that changes to the water table and outflow points usually involves enhanced permeability near the surface and more rapid drainage of near-surface water rather than water being 'squeezed out' from great depth.

C.131 I am not persuaded that the examples given by objectors, notably by Greenpeace, of major earthquake-generated surface discharges of groundwater are indicative of what could happen at Sellafield within a PCSA timescale: I consider they are in quite different geological settings and the American examples in particular involve large magnitude seismic events on normal faults in an undoubted extensional stress regime.

C.132 Climate: Although local meteorological records are being studied and the climate record assessed, it is long term global climate changes that are likely to most affect groundwater flows, either directly by changing precipitation and net recharge, or indirectly by affecting sea levels or inducing ice cover or permafrost conditions. The Nirex research is just part of the worldwide effort being put into understanding global climate change and effects, whose scale and degree of international consensus are such that I consider the Nirex climatological work and assessment of consequential effects on landform evolution is more soundly based than many other areas of its scientific programmes.

C.133 The climate record over the past hundreds of thousands of years is becoming well defined from studies of seabed sediments, ice cores etc. Progress is being made on models of global climate systems that combine the behaviour and responses of the atmosphere, oceans, ice and land cover, and biosphere. Nirex has an active role in running one such international model [COR/527, Box 6] which appears to give a fair simulation of past conditions despite not yet including greenhouse gas effects and deep ocean circulation. The company has identified five broad climate states, four of which (Temperate, Boreal, Periglacial and Glacial) have been experienced over the last million years or so and a fifth (Mediterranean) may result if global warming prevails, and has selected analogous locations to represent the variability with time within each [ibid, Box 5]. It proposes to represent future climate change in terms of sequences of these five climate/biosphere states, and has developed two possible sequences over the next 125,000 years [ibid. p.23], with and without enhanced greenhouse gas warming, to reflect the range of possibilities generally accepted by the international community. To jump from one state to the next is obviously a great simplification but the successful refinement of the global climate model should permit a more continuous representation if required. Of course climate change over longer periods would require a different approach, and must involve 'qualitative reasoning'.

Priorities for further work programmes

C.134 Whilst it is not necessary to produce a precise deterministic characterisation of all aspects of the Sellafield Site geology and hydrogeology there is a need to improve the detail and interpretation of geological structure and stratigraphy across the PRZ. Nirex is considering an extension of its 3-D seismic survey although it believes the added definition provided by the survey may have no relevance to the hydrogeological modelling. However as at least general associations can now be demonstrated between physical and hydraulic properties and particular stratigraphic and structural divisions, I consider that additional detail on a smaller scale should assist modelling, stochastically or otherwise, on the wider scale. Continued site investigation and testing should extend to depths and stratigraphic units deeper than the currently favoured provisional repository horizon (the relatively fractured Fleming Hall Formation at around 650m bOD) if an adequate comparative assessment of the BVG basement rocks within the volume of the PRZ is to be made.

C.135 There is a need for more boreholes to define further in three dimensions the geological sequence and hydrogeology (groundwater heads, density and salinity distributions and other water chemistry parameters) over at least the Site area. Nirex proposes up to 4 additional boreholes (nos.15-18) west and NW of the PRZ to investigate the saline transition zone and its influence on groundwater flowpaths; further drilling east of the PRZ around BH 9 to investigate groundwater recharge; and up to 2 holes south of the PRZ between nos. 2 and 11, possibly by inclined drilling from the BH 11 site, to explore the hydrogeological influence of the Seascale Fault Zone. The effect would be to achieve quite close monitoring over an area of about 3km squared centred on the PRZ, with just over 20 boreholes, and more scattered coverage beyond. All the new holes would be appropriate and useful but would still leave significant areas relatively unexplored when it comes to defining the boundary conditions of even a small 'regional' 3-D hydrogeological model of say 10km squared. A fairly well defined NE-SW cross section can be drawn from BH 8, through the middle of the PRZ to the shore at Sellafield Works but not for example a parallel section only 1½ or 2km to the NW, just beyond the PRZ, since there are no holes in the supposed recharge areas north and NNE of the PRZ nor between there and BH 7.

C.136 I consider that insufficient is yet known about the coastal groundwater discharge zone and its geology, and the hydrogeological consequences of changes in sea level, particularly a significant fall. I am aware that drilling offshore is considerably more expensive than on land and presents problems for long-term testing and monitoring but in my view it would be difficult to make a reliable safety case without the data from at least one and preferably more boreholes beyond the present coastline. There is also a strong case for a more systematic investigation, prior to disturbance by the RCF, of groundwater head and possible water chemistry differences across the major faults, especially the Fleming Hall and Seascale fault zones, but it would be costly: as many as 3 or 4 pairs of holes, additional to those existing or proposed, could be requisite. In these respects my views are similar to those expressed by FOE.

C.137 All or almost all of the boreholes noted in the previous two paragraphs would be beyond the PRZ so the data they would yield could not be obtained from the RCF. It would be essential that any within potential direct influencing distance of the RCF are drilled and allowed to recover prior to the start of RCF shaft sinking.

C.138 There is a need to establish general baseline hydrogeological and hydrochemical conditions over the Site area prior to construction of the RCF. I consider that Nirex is close to settling baseline head data, even in the holes affected by the RCF3 pump testing, though monitoring in the BVG would need to be continued for as many years as some boreholes in the Triassic sandstones if any response to trends in annual rainfall is either to be recognised or discounted. As for hydrochemical data, although the broad composition and distribution of groundwater attributable to the different regimes are now relatively well understood, there is a need for better coverage over the Site area. Moreover, repeated sampling and testing are required to give confidence that the samples are the least contaminated that are practically obtainable. Until recently at least Nirex's contractor was unable to make a complete enough 'best estimate' for in situ groundwater composition for the purpose of modelling water/rock interactions because of uncertainties over natural temperatures, pH and Eh [CCC/4/7, 2nd page]. However it is likely that some uncertainty will remain over in situ Eh and pH conditions if samples are obtainable only from deep boreholes. Close access to BVG groundwater in the RCF would improve the chances of being able to obtain uncontaminated samples of more precisely known source.

C.139 The major task is to develop a much better understanding of groundwater flow and hydraulic conductivity in the Sellafield strata, particularly the relationship between fracturing and groundwater flow in the BVG and variations in the distribution and magnitude of in situ permeability within that group of rocks. There is a need to characterise and measure flow in fracture networks in three dimensions over lengthscales of tens to hundreds of metres and look for associations with, for example, faulting, rock type, stress direction or cooling contraction joints. In addition the possibility of local fairly direct hydraulic connections between the BVG basement and overlying sandstones has not yet been adequately confirmed or discounted.

C.140 Although further borehole pumping tests and cross-hole hydraulic testing could be carried out and would assist with these matters, they would be no substitute for the RCF, which would provide close access for direct observation and logging of the rocks and permit tracer tests at a variety of scales and orientations to give indications of rates and paths of flow, and of diffusion, sorption and accessible porosities. The RCF would also enable the response to be observed to large scale and prolonged drawdown, both radially around the excavations and between the fracture networks in the BVG and the more porous strata in the cover sequence.

C.141 The evidence of groundwater residence times and the age of fracture systems could play an important part in making a satisfactory safety case for a repository at Sellafield. More determinations are needed of stable isotopes, noble gases and other specific indicators of age for groundwater samples drawn from boreholes over a wider territory. Coupled with the use of other geochemical species they may help identify long-term flow patterns and flow history. The RCF would also provide opportunities to obtain high quality water samples for palaeoindicator testing. Further mineralogical research can be done on the dating of faults and the evolution of the fracture systems as a guide to the most recent tectonic activity and more especially the extent to which the fracture network flow has remained stable over geological time. It requires the sampling and testing of fault and fracture infill materials. The RCF would afford good opportunity to sample from fractures but give more limited access to fault zones, which may continue to be best explored by deep cored drillholes.

C.142 The evidence suggests that considerably more experimentation and model development is needed on radionuclide solubility, sorption and general thermodynamic relationships over the range of temperatures and chemical conditions relevant to a Sellafield repository, from natural groundwaters in the distant geosphere to the special conditions in and around the degrading waste and repository chemical barrier. Much of this would appropriately be laboratory-based work, including sorption experimentation but sorption data need to be specifically related to the local rock types. Tracer experiments would be useful but would have to await the RCF. The RCF would also give the best opportunity for sampling groundwater for any natural colloids and perhaps for experiments on colloid transport through the fractured BVG. Similarly for research on gas migration and its potential effects there is no substitute for practical in situ experimentation and investigation in the intended host rocks.

C.143 Various aspects of repository construction and performance cannot easily be advanced without the opportunities afforded by a facility like the RCF: the geotechnical properties of the rocks and superficial strata could only be explored by observing the body of materials at close quarters in substantial excavations; measurement of excavation disturbance of the rocks and consequential hydrological effects require RCF-scale excavations in the potential host rocks; and meaningful testing of techniques for plugging and sealing excavations and controlling groundwater inflows must also be done in the intended host rocks under conditions comparable with that of a DWR.

C.144 There is a general need for the Nirex science programme to be advanced on all fronts, of which one important area would be the development of climate scenarios and how future climate states may affect landforms, the physical and hydrological properties of the geosphere, and the biosphere.

D MODEL DEVELOPMENT

Principles and Methodology

D.1 In this section I consider aspects of the models, mostly numerical and mathematical, used in performance and safety assessment to represent the various elements of the proposed waste disposal system and its environment, and the system as a whole. Such models are designed to aid understanding and facilitate calculations and prediction of processes and behaviour. The term 'model' is also used in a rather different sense to describe interpretations and representations of data, for example the synthesised information on the geological structure of the PRZ [COR/530]. The latter is in effect a 3-D digital map of the ground surface and various geological boundaries, including the planes of the principal faults and the top surfaces of major stratigraphic units, produced by interpolation between data points derived from borehole intersections, seismic tomogram interpretations, etc. [paras. C.6-11 above]. The model permits, for example, the rapid production of cross sections, structure contour maps and 3-D visualisations, but does not itself have a predictive ability. However the dimensional data in this model is the starting point for the construction of the 2-D and 3-D geosphere flow models noted below.

D.2 Transport by groundwater is recognised as the most important potential route by which radionuclides from waste in a deep repository might be carried back to the near surface so it is appropriate that intensive effort has been put into the development of hydrogeological models to help form an understanding of the Sellafield potential repository site, to test the feasibility of concepts and whether they match observational data, and to develop predictive tools that can reliably assess the future behaviour of the disposal system. Models are also used to test the significance of parameters and sensitivity to change, and to identify data requirements.

D.3 Groundwater models inevitably entail simplifying assumptions: because the natural world is so varied and complex that it can never be fully characterised and represented, and the aquifer structure and boundaries cannot be fully known; not all features or processes are of practical significance; and in order to keep the problem tractable. Because the Sellafield district is geologically and hydrogeologically complex, the task of constructing conceptual models and of adequately representing that variability is a particularly difficult one.

D.4 The development of a groundwater model starts with the creation and development of a conceptual model of how the system or process operates: then come in sequence the expression of that hypothesis as a numerical model and computer code; the input of measured or estimated data to run the model; the calibration of the model to better match observations; and an attempted validation of the model by testing predictions against new data. These are followed by additional cycles of model development, calibration and attempted validation as necessary until a sound and sufficient model emerges. COR/510 [p.3 Box A] describes a conceptual model of a hydrogeological system. Models have been created for a wide variety of other elements that will be considered in making a repository performance and safety assessment, from corrosion mechanisms of waste containers [COR/529, p.17 Box 8], to climatic cycles related to the planetary motion of the earth [COR/527, boxes 1 & 6], to future patterns of agriculture and settlement under a changed climate state [COR/526, Box C].

D.5 In the specific context of the Sellafield project Nirex has developed a hierarchy of models [see COR/510, fig.1] starting with the building of an overall conceptual model of the district; then adoption of numerical models of differing types (2-D & 3-D; analytical, porous medium and fracture network) to represent effective properties of the rocks; then 2-D & 3-D local flow models (of fracture network type) and more regional flow models (of porous medium type); and finally preliminary safety assessment models (sampling from PDFs) with a network of 1-D transport submodels.

D.6 FOE considers that just one model should be developed to address all aspects of groundwater heads, flow and chemistry across the region. By contrast the Nirex Review Panel (Annual Report 1994) thought it a positive requirement to 'continue to develop an approach to modelling which utilised a range of techniques', with simpler models to investigate alternative concepts and carry out scoping calculations and complex models to provide input parameters to safety assessments [COR/516, s.3.2]. Nirex reports describing the work [eg COR/510, -517, -521 & -522] show that the company's modelling builds on earlier models, and uses one type of model to cross-check another, or to provide input data for another, or to test the significance or sensitivity of a particular feature or parameter. This is a proper and thorough approach to modelling for a project of this importance and involves very much more rigorous procedures than in say conventional aquifer or waste disposal studies.

D.7 The level of detail in any particular model needs to be appropriate to the purpose. Initially the approach may be relatively simple, for the purposes of making scoping studies, establishing orders of magnitude, etc. The models will gradually build up and become more refined. As the time approaches to make detailed safety assessments I would expect more integrated models to be used, but I consider it will still be appropriate to use separate models with differing degrees of detail to demonstrate the anticipated performance of parts of the system and the system as a whole under time-variant conditions. It will never be practicable to acquire the relevant data and incorporate the same level of detail towards the boundaries of a region-wide model as for the area of greatest interest, in this case the PRZ, nor will it be necessary to do so since only key input parameters or constraints are relevant at the boundaries. On the other hand, those boundary conditions do need to be defined and modelled with confidence.

Current stage of Nirex's regional and fracture flow modelling

D.8 The overall conceptual model of the site as a whole, with seaward dipping layered sediments over hard basement rocks, disrupted by geological faults and containing three distinguishable groundwater bodies with zones of mixing between, has been developed considerably on the basis of 2-D models representing vertical cross sections through the simplified and idealised geological sequence to depths of several kilometres. Two-dimensional areal models were used at an early date in the Sellafield studies to obtain an indication of the overall water balance, head distribution and general flow pattern in the sandstones and assisted in selecting a NE-SW line of section through the PRZ considered representative both of the general dip of the strata and direction of groundwater flow. This work has subsequently been complemented by 3-D model calculations.

D.9 It is a question of practicality that 2-D models are used for many purposes in preference to 3-D: it is time consuming to set up the matrices of points or cells and to input all the parameters, and 2-D models can include considerably more detail than 3-D. Nirex considers that the approximation involved in representing the 3-D flow system by a suitably chosen 2-D model is much smaller than current uncertainties in many of the hydrogeological parameters.

However a good understanding and appreciation of the system in three dimensions will undoubtedly be necessary in order to make detailed repository performance assessments.

D.10 Flow models: Numerical models for flow in rock masses can be broadly divided into those based on continuum analogy (similar to flow through a porous medium), or discontinuum (through discrete fractures), or hybrid models combining elements of both. A good summary of the available methods and their current state of advancement is given in FOE/6/21, section 2 & figs. 2 & 3. It takes account of research being carried out in the field of deep disposal of radioactive waste in hard rocks, including projects with which Nirex is directly concerned.

D.11 Fluid flow in the prospective BVG host rocks at Sellafield is thought to be almost entirely through fractures, and in the overlying SSG predominantly through fractures, so the ability of adopted models reliably to simulate and predict flow through fractured rocks is essential. I accept the conclusions reported in FOE/6/21 [s.6, 1st & last paras.] on the current understanding of fluid flow through fractured rock, the limitations of the various modelling methods and the difficulties of obtaining adequate field data. Among these are that:
- the physics of fluid flow in the fracture network of fractured rocks is not yet well understood, particularly in fractured low permeability rocks;
- models of the discrete network type ought to be best for rock hydraulic modelling but discontinuum methods suffer from lack of information of real 3-D geometrical distribution of fractures so construction of realistic models is not possible;
- equivalent continuum and hybrid models are practical and adequate tools for the investigation of flow in rock masses; but
- continuum methods cannot (alone) answer whether short cut flow paths to the biosphere are possible.

Moreover, [ibid., s.2, 1st para.], it is usually assumed in these models that the rock mass is rigid whereas in reality its hydraulic properties are also affected by stress and temperature [see D.19 below].

D.12 The two principal computer models used by Nirex for groundwater flow are NAMMU and NAPSAC. NAMMU is of the continuum permeable medium type and is used to model flow in 3-dimensions up to the regional scale of tens of kilometres in lateral extent (although more usually applied in modelling flow in 2-D sections across the district); NAPSAC is a fracture network model used to calculate 3-D flow local to the proposed repository. Nirex contractors have used both in a number of international modelling projects to gain experience in their application. Both are reasonably described as state-of-the art models of their type and are significantly more complex and sophisticated than most general groundwater modelling packages.

D.13 Porous medium modelling: On a district or larger scale it is appropriate to use a continuum model such as NAMMU to approximate the fractured medium, provided the parameter values can be, and are, 'upscaled' appropriately. Such models require the input of effective parameter values for permeability, porosity, etc, representing an average or integral of the physical values, to make the simplified model best represent the field data, if such values can be obtained on a large enough scale. In applying a continuum porous medium model to a fractured body of rock like the BVG it is assumed that above a certain 'representative elemental (or elementary) volume' (REV) the variation in distribution and properties of the background fracture system become insignificant and the fractured mass behaves as an equivalent porous mass.

D.14 There is a difficulty in defining any particular representative elementary volume, because REVs exist at different scales according to the magnitude and connectivity of discontinuities under consideration [FOE/6/21, p.4, paras 5 & 6]. Nirex notes that in the Stripa 'site characterisation and validation' experiments it was possible to define a REV for the fracture network (typically 12m) whose properties were fed into porous medium models [NRX/15/33, p.211, 1st para.], and considers that for the BVG of Sellafield the REV is likely to be of a few tens of metres, small in comparison with the depth and dimensions of the deep repository system. However the borehole hydrogeological tests show marked heterogeneity even on the coarse scale of pump tests over 50m intervals. The volcanic rocks at Sellafield show rapid lithological and stratigraphic variations vertically and laterally, are well faulted and jointed, and may show irregular domains of cooling joint systems as well as tectonically induced joint sets. In such ground it will be particularly difficult to define average properties at appropriately large scale.

D.15 With porous medium models the effective permeability and resulting flow must represent an 'average' for a block. Effective permeability and dispersivity parameters determine the spread and mean speed of transport of, for example, radioactive solutes through the rock mass but the Royal Society report has highlighted the difficulty of modelling the circumstance in which groundwater flow is preferentially channelled through only a small proportion of the fractures, as could well be the case in the BVG, so giving rise to a channelling type frontal growth [COR/605, fig.8.1]. This would appear to be a serious shortcoming in the applicability of NAMMU to the BVG and a reason why more emphasis is needed on fracture flow models.

D.16 Fracture network modelling: The fracture network code NAPSAC is used to model and investigate groundwater flow through the background fracturing of the BVG. Like most similar codes, it assumes a fluid of constant density and an impermeable rock matrix.

D.17 FOE says that fracture models such as NAPSAC do not reflect real patterns of fractures, but they are not intended to. It is never possible to describe deterministically all the fractures in even quite small volumes of rock so such models use a stochastic approach to represent the spatial variability of the flow system. They create computer generated synthetic networks of simple rectangular forms but with properties based on statistical distributions of the measured characteristics of conductive fractures at the site, such as fracture frequency, orientation and extent, transmissivity and storage capacity. Many realisations of the fracture system are created, by sampling from the measured property distributions, to arrive at calculated output values (such as hydraulic conductivity at various length scales or heads) that can be compared against further site measurements. However the difficulty of obtaining adequate and representative data on the distribution and hydraulic properties of BVG fractures from deep boreholes and surface mapping is one of the principal reasons why Nirex seeks to have direct access to the host rocks in the RCF.

D.18 FOE/5/8 [s.3] describes NAPSAC, which can generate up to 50,000 intersecting fractures and track the paths taken through the network by up to ½million particles. This sounds a large number of fractures but depending on the fracture frequency it may represent a cubic volume of rock of sides well less than 100 metres. If larger volumes are to be represented then it appears that the model is further simplified, by assuming zones of fractures between which are substantial unfractured blocks of rock. Nirex describes having now implemented a linked NAMMU and NAPSAC model, combining a fracture network system below and porous medium above [COR/510, p.20 & Fig.7], which is indeed a useful advance but appears to be restricted at present to similar numbers and distributions of fractures.

D.19 Coupled models: The preliminary safety assessments described to the inquiry are based on hydrogeological models that assume the geosphere to be at uniform temperature, but a detailed model will need to take account of the natural geothermal gradient (which may not be uniform across the district because of proximity to deep granites) and the heat generated within the repository, which may induce convection flow. Heat, rock stress and water flow are interrelated and can be linked in coupled thermo-hydromechanical (THM) computer models [FOE/6/22, fig.1 & COR/605, s.8.2.5]. Temperature influences flow because it affects the density and viscosity of fluids, and alters rock mass volume which in turn affects fracture width, etc.. Temperature also affects chemical equilibria and rates of reaction. Flow influences the dissipation of heat. Similarly the characterisation of strata permeabilities is based on current in situ rock stress conditions, but changes in stress, caused for example by ice loading, could also affect crack widths. Such factors are not normally important in groundwater modelling but assume significance given the barrier function of the geosphere and the design timescale of a DWR.

D.20 The state of progress with coupled groundwater flow models can be gauged from a recent review of the DECOVALEX project [FOE/6/22]. It describes how numerous numerical models and computer codes being developed by leading international research teams concerned with nuclear waste disposal were compared and benchmark tested against a small two dimensional model around a notional repository vault. An impression of the variety of alternative computational models and fracture concepts considered is given by ibid. fig.8. The report observed that the relationship between the physical properties of fractures and water flux is the least understood of the coupled processes [ibid., p.11 last para. & p.20 para.5]. The Royal Society report [COR/605, s.8.2.5] also stressed the relatively early stage of development of coupled THM models and the lack of experience in applying them in field situations, the difficulties of obtaining the relevant field data, and complexity of scale-up issues. I agree with Nirex that taking account of geothermal and similar coupled effects does not amount to the introduction of a completely new conceptual model, since flow is driven predominantly by gravity and density differences, but in my view Nirex has understated the work to be done on coupled models and the difficulties of incorporating these into the overall model.

D.21 A related matter is modelling of flow in the excavation disturbance zone where changes in rock stress patterns result in altered groundwater flow characteristics. Practical experience in other rock laboratories has demonstrated the need for better understanding of the mechanisms involved as well as improved numerical modelling [see C.113].

D.22 Gas flow modelling: There appears to be a well developed computer model for estimating the generation of gases in the repository [COR/509, section 2] but as for how gas might migrate through the geosphere no more than scoping studies have been made. Fairly well developed models also exist for the behaviour of radioactive and flammable gases and routes for human exposure once they reach the biosphere [ibid., section 4], but are academic if geosphere modelling is unable reliably to predict when, how and in what quantities gas might escape through the strata. Most geosphere gas migration assessment work to date has concentrated on the far field, which has been judged to be more important for the performance of a Sellafield repository [ibid., p.10 right]. A number of migration mechanisms have been considered - some gas would be in solution but most would probably be as bubbles or continuous streams of free gas - but the possibilities are couched in speculative terms [ibid., s.3.1 & 3.2]. Scoping studies have been made assuming simple Darcy flow and flow through notional 'capillary bundles' [ibid s.3.3(a)] and in more detail with an oil reservoir simulation program using a two-phase porous-medium flow model [ibid, s.3.3(b), p.15], but all this work is acknowledged as being based on few pre-existing data in water-saturated fractured rock (from anywhere, let alone Sellafield) [ibid., s.3.4]. Even less is known about gas migration in EDZs. In situ observational and testing data are prerequisites to meaningful modelling of gas flow through the geosphere [see C.108 & .110 above] but are seriously lacking for Sellafield. The RCF would provide an opportunity to carry out direct experimental studies.

D.23 Modelling of faults: Nirex groundwater flow modelling has adopted four categories of rock permeability, from matrix porosity (Type 0) and background fractures (Type I) to organised structures of fractures (Type II from 50m to 5km in length, and Type III of greater length) [COR/522, v.1, s.5.1.1]. Faults fall into categories II or III according to the length of their surface trace: no distinction has been drawn on the basis of, say, magnitude of displacement, or orientation, or style of throw (normal or reverse). In the vicinity of Sellafield the only faults represented as Type III features and explicitly modelled are the Lake District Boundary Fault Zone, Fleming Hall FZ and Seascale FZ, on the line of typical NE-SW cross sections, and the Woodland FZ 5km to the NW. I have already expressed the view that fault F2 also appears to meet the criteria to be defined as Type III although not modelled as such [para. B.97 above].

D.24 Nirex accepts that the major faults may be sufficiently variable for each to require a different modelling approach [COR/522, v.1, foot of p.5.9]. In FOE/5/19 the FHFZ was modelled in NAPSAC as a 200m wide network zone of zones of locally enhanced conductivity [p.18 para.2 & fig.2.1]. Nirex 95 suggests alternative conceptual models, for example halos of fractures each side of a core zone, or a sparser network of long fractures with short cross connections [COR/522, v.1, figs. 5.2(a) & (b) & s.5.1.1 pp.5.2 & 5.3]. Type III features in the BVG were modelled in the former manner and of some hundreds of metres in total width [ibid., v.1, pp.5.9 & 5.10; & v.3 fig.2.4] but the Seascale Fault Zone was considered more complex [ibid., v.3, fig.7.18]. Nirex believes the Seascale FZ may actually be a barrier to flow [ibid., v.1, s.5.1.3]. Clearly it is highly significant whether the faults have an effective permeability greater or less than that of the surrounding basement rock [see COR/521, fig.3.10], as exemplified by Nirex 95 variant calculations for the SFZ [compare COR/522, v.3, figs.2.7, 7.19 & 7.20]. There appears to me to be little firm understanding of the real nature of these larger features, or even whether they are indeed zones of enhanced conductivity.

D.25 Transient conditions: In order to make an adequate post-closure performance assessment, groundwater flow modelling will need to be able to examine and predict the effects of transient change in the major factors of climate and landform. Changes in sea level, for example, may produce rapid responses in the more permeable shallower strata but very slow changes in the low permeability basement rocks, so measurements of heads and water chemistry in the former may reflect current processes and boundary conditions whereas pressures, and particularly water chemistry in the deep BVG, could well reflect conditions in the distant past. Indeed it is probable that the deep flow system is not in steady state.

D.26 The basis of the preliminary performance assessments has been the definition of scenarios that describe the initial state of the near-field, geosphere and biosphere and the evolution of the system. Risks to humans and the environment are calculated for each scenario taking into account the probabilities of occurrence of the relevant events and processes, and uncertainties in predicting their consequences. Each major alternative scenario, i.e. state of climate and sea level for the Sellafield coastal region, has been represented by steady state models maintaining those conditions throughout the modelled time period. Steady state models, as used in most Nirex work to date, can be run for any chosen future time period. Nirex adopts four time frames for its PCPAs: to 100 years, to 10,000 years, to 1 million years; and to 10^8 years. The computer calculations are made with the same level of detail throughout the period selected despite the increasing uncertainty, so there is a risk of giving a misleading impression of accuracy in figures calculated for those distant times. Over such extended timescales 'multiple and complementary lines of reasoning' would be necessary instead [HMP/1/1, para. 9.5].

D.27 It would be more realistic to reflect these major changes in climate and geography, and all associated changes in conditions and processes from the repository to the biosphere, using time variant models capable of varying input parameters as the computations progress through steps in time. These might instantly jump from one set of scenario parameters to the next, at predetermined intervals of time, or by generating progressive changes coupled to, say, climatic parameters. The Royal Society study group thought that attempts to generate scenarios by identifying combinations of appropriate features, events and processes and interactions between them, then developing models to deal with the combinations and interactions, are unlikely to be successful in the near future and that more rapid progress might be made by a holistic approach, starting with consideration of climate change and other driving forces for the evolution of both geosphere and biosphere conditions [COR/605, p.91, 3rd para.]. It is my impression that the development of conceptual models for incorporating these major transient factors is still at an early stage and that appropriate numerical models have yet to be developed.

D.28 Vulnerability to disruptive events and intrusion: Any PCSA will need to consider the vulnerability of the repository to significant damage and uncontrolled radionuclide release as a result either of natural external events, such as severe earthquake or meteorite impact, or of human intrusion, such as deliberate sabotage or inadvertent penetration by mineral exploration drillholes. In general these possibilities are less amenable to detailed modelling than they are to statistical expressions of the likelihood of an actual incident and to broader scoping studies of the consequences.

D.29 To assess the incidence and magnitudes of seismic events Nirex has studied the geological and historical record and has its own seismograph stations to supplement the national and wider network [see C.19 & C.122ff]. As for assessing the potential effects of seismicity, Nirex places emphasis on analogue events [NRX/15/2, p.19]. A mined gallery substantially filled and grouted would ordinarily be thought of as relatively insensitive even to severe earthquake vibrations, and at present Nirex discounts the possibility of actual displacement on any of the faults in the neighbourhood of the PRZ; more probable is a change in the hydrogeological properties of the host rocks as a result of changes in the regional rock stress field but much work still needs to be done on understanding fracture flow through the BVG basement rocks in their present state before any serious attention can be given to transient seismic effects or the consequences of more permanent tectonically induced stress changes. Assessment of the incidence and effects of other natural disruptive events, such as periods of erosion [ibid., s.5.1], takes account of evidence of the geological past and, in the case of meteorite impact, I would expect astronomical observations too.

D.30 The assessment of likelihood of human intrusion events appears to be based on experience of human behaviour and activities, and a qualitative appraisal of geological and other natural resources in the locality [NRX/15/2, section 3]. As for the consequences of intrusion scenarios, Nirex draws a distinction between the direct exposure of individuals associated with the intrusion event itself, and the delayed environmental consequences of past intrusions [COR/526, s.4.5]. Calculated direct risks are derived from assumed scenarios about the human actions and contact with contaminated materials [eg NRX/15/2, Box F]; the indirect effects are assessed assuming similar groundwater pathways and radionuclide distribution processes to those used in regular repository performance modelling [ibid., p.15]. Particularly mentioned is the risk that water supply wells might intercept or draw in radionuclide-contaminated groundwater [ibid., Box F & COR/526, s.4.5]. Nirex anticipates that an extensive contaminated region of the geosphere might develop downstream of a repository, as shown schematically on NRX/15/12, fig.1. (This example assumes sea level remains as now.)

Relationship between flow models and PCSA models

D.31 Nirex needs to model every element of the potential chain from waste disposal, mobilisation in the repository, passage through the surrounding rocks and transport to the surface environment so as to make post closure performance assessments and post closure risk assessments. This whole system is broadly divided into the 'near field', 'geosphere' and 'biosphere'. Modelling for post closure safety assessment purposes is carried out using the program MASCOT, which comprises a suite of sub-models to quantify the release of radionuclides from the repository, their transport through the geosphere and distribution in the biosphere, where the activity of residual radionuclides can be expressed as dose rates [COR/507, pp.5-9 & COR/529, Box 21]. Probabilistic methods of assessing risk such as MASCOT, using 'Monte Carlo' random sampling from distributions of relevant parameters, are an appropriate and widely used approach to dealing with uncertainties.

D.32 The MASCOT computational methods do not cater for transient models where parameters vary with time, but a detailed safety case will need to account for the effects of inevitable climatic and other change, at the appropriate level of detail, over the whole period for which the repository may pose a significant radiological risk [see D.25-27].

D.33 In modelling the near field there are simplifying assumptions - for example, that after a period of absolute waste containment the repository becomes instantaneously saturated, that radionuclide solubility and sorption parameters remain constant throughout the assessment period [COR/529, s.2.3], and that the flux of each radioelement into the geosphere, the source-term, is governed by its solubility limit and sorption coefficient [ibid., s.3.3]. Such assumptions will need to be refined well before the time to make a detailed safety case.

D.34 Limitation of radionuclide releases from the wastes into groundwater relies largely on chemical containment, but the rate of flow of groundwater through the repository affects the rate of change of properties of the backfill and waste, rates of solution, pH, etc and the rate of radionuclide transport within and out of the repository, as reflected in the parameter 'source term spreading time'. If flow through the repository increases the source term spreading time shortens. NAPSAC fracture network modelling results are used as an input into the MASCOT near field sub-model.

D.35 That part of the MASCOT model concerned with radionuclide transport through the geosphere simplifies calculations to networks of one-dimensional submodels with different parameters in various hydrogeological units and whose path lengths, travel times and groundwater discharge rates are based on the output data from the multi-dimensional NAMMU & NAPSAC models. Although a 2-D porous medium NAMMU model [COR/510, fig.3(b)] might predict an irregular path of water flow through successive hydrogeological units from the repository to geosphere [ibid., fig.4], MASCOT assumes that in any particular unit the flow follows a series of parallel 1-D paths. A version of MASCOT is available which models a 3-D network of 1-D continuous media flow paths and which the Royal Society study group thought may have advantages for improved modelling of the geosphere/biosphere interface and may be easier to integrate with the broader-brush 3-D groundwater flow modelling [COR/605, p.141 upper right].

D.36 I understand that 1-D transport models were developed because of the difficulty of modelling in 2 or 3 dimensions the migration and decay of actinide chains, with members each having differing radioactive half-lives and sorption behaviour. The 1-D calculations take account of longitudinal dispersion, radioactive decay, retardation due to sorption and rock-matrix diffusion along the pathlines, but neglect transverse dispersion which is asserted to be usually small [COR/510, Box H]. Uncertainty over the appropriate sorption values has been mentioned previously [C.91-98]. The processes of diffusion and dispersion can cause migration of radionuclides away from the flowpath. Nirex says that diffusion in pores and fractures is generally very small but dispersion, caused by heterogeneities in the flow field within individual channels and between flow channels, leads to much greater spreading [COR/510, p10, Box G]. It seems to me that there is considerable uncertainty over the effects of dispersion but the spread of the repository radioactive leachate plume is highly relevant to safety assessments. Nirex describes how dispersion parameters were inferred from general literature values [COR/522, v.2, s.5.12] and points out the wide scatter of values for longitudinal dispersion, especially at the distance scales relevant to Sellafield [ibid., s.5.12.1 p.5.20 & fig.5.9]. The effect of transverse dispersion in the plane of the 2-D cross sectional models was explored using a finer-grid finite-element model in the context of agricultural well risk calculations and can be seen to have a marked effect for the cases modelled [COR/522, v.3, s.2.3 & figs.2.11 & 2.12].

D.37 The validity of the probabilistic 1-D radionuclide transport modelling and whether it can adequately quantify uncertainties in patterns and rates is difficult to demonstrate. The Royal Society report [COR/605, s.8.4.1 p142] suggests a comparative study between MASCOT geosphere transport calculations of the present type with (3-D) models of the level of complexity of NAPSAC and NAMMU, perhaps also including a more complex representation of sorption and rock-matrix diffusion than in MASCOT. As for obtaining data against which to test the models, tracer studies in the RCF would be useful but it is difficult to see how they could cope with large scale heterogeneities in the host rocks.

D.38 MASCOT has submodels for groundwater passage through fault zones [ibid., v.3, fig.4.1]. It derives its parameters for flow through these supposed major zones of locally enhanced conductivity from a series of calculations using NAPSAC models [FOE/5/19, fig.3.1 (cf.COR/507, fig.3]. It is assumed that Type III features effectively comprise a network of closely spaced transmissive Type II features so effective parameters of the former are inferred by extrapolation from analyses of effective parameters of the latter with slight adjustments [COR/522, v.2, 5.1.6]. Separate effective hydrogeological properties are assigned to the halo and core of Type III features [ibid., v.3, table 2.1]. Assumptions made about the hydrogeological properties of the fault zones greatly affect flow pathlines and transit times and hence the MASCOT calculations of degree of risk and/or date when the peak risk occurs, as demonstrated by the Seascale Fault Zone variants, but it seems to me that there are still great uncertainties about almost all aspects of modelling the mapped faults: how to categorise them, how to represent them conceptually, what effective properties to assign to them, and so on.

D.39 In the case of biosphere research I note that although fresh work is being undertaken, the large size of the databases and the existence of well-established, usually radionuclide specific, values for many parameters are just two reasons why single values of parameters have to date been used in the biosphere part of PCPA calculations rather than sampling from PDFs [COR/605, s.9.2]. But Cumbria points out the uncertainty over subsurface routeing of radionuclides once they reach the biosphere. The factor 'S' represents the assumed proportion of radionuclides reaching the surface soils and was taken 'conservatively' in Nirex 95 to be 0.1 (i.e. 10%) for Temperate and Boreal resource areas [COR/522, v.3, p.5.12 top] but recent research estimated a value closer to 0.2 [NRX/15/4, conclusion]. If this is substituted in the risk calculations then variant models [as in COR/522, v.3, table 7.7] would exceed the risk target. This demonstrates the importance of reducing uncertainties in input parameters and shows just how uncertain still are some of the more tangible and straightforward parameters.

Treatment of Uncertainty

D.40 Uncertainties and imprecisions arise at all stages of the investigation, sampling and testing, modelling and assessment of a site. Uncertainties and bias in data introduced by measurement techniques have been taken into account by formal elicitation of PDFs of key parameters which are then sampled to populate models, but the steps being taken to formally quantify basic geological uncertainties, such as accuracy of resolution of faults and significant stratigraphic units using seismic tomography, are less clear cut. Nirex has used techniques such as section balancing and structural restoration (i.e. seeing whether the computer can return the rocks to a pre-faulted condition) to arrive at preferred interpretations out of a number of alternatives but selected models may not be the closest to actuality.

D.41 Cumbria draws attention to the phenomenon of 'dilution of risk' in safety assessments. Nirex 95 notes that for mean risk the results from probabilistic calculations generally give broader curves than from deterministic calculations [COR/522, v.3, p.6.14 top]. The example is given of the flattening of the ^{36}Cl risk in the probabilistic case [comparing ibid. figs. 6.8 & 6.13]. The argument is that when a Monte Carlo simulation is done, in this case sampling from PDFs that express uncertainty in the magnitude of the peak and uncertainty as to when the peak will arrive, the combination will flatten the time/risk curve, i.e. dilute the risk. This phenomenon does appear to me to be generally the case when ranges of probabilistic risk are combined and is one of the reasons why it is appropriate to compare outputs from deterministic and probabilistic models, as practised by Nirex. The disparity between outputs will reflect the degree of uncertainty in input values.

D.42 Nirex suggests, as in its Probabilistic Safety Assessment overview report [COR/507, p.4, 2nd para.], that:
(a) in principle, uncertainty with regard to choice of models can be dealt with in much the same way as parameter-value uncertainty, so that provided degrees of belief can be attributed in a defensible way to alternative models, then random sampling may be used in just the same

way as for parameter values; and
(b) it is often possible to consider alternative models as members of one all-embracing model, with the values of some parameters effectively determining the choice of the more particular model; or
(c) it may be possible to set the distributions for the parameters of a single model in such a way as to produce a range of outputs encompassing those that would have been produced by alternative models.
As for (a), random sampling between alternative models, I am sceptical. By definition, if degrees of belief need to be invoked then the degree of validation of the models is in question. At the present stage of progress in modelling it may well be that for a particular application a number of conceptual models and computational methods are being applied and each gives a fair match with observational data and shows promise as a predictive tool. In those circumstances, degrees of belief in individual models may assist in constructing elicited PDFs. If, closer to the time of making a detailed PCSA, there is still uncertainty as to which is the most appropriate and best validated model to use, then it seems to me that the one in which there is the greatest belief should be incorporated in the overall model but that the performance of each should be separately presented as part of the 'multiple lines of reasoning'. This approach, though, would only be acceptable for the longest timeframes [see D.26]. As for (b), I accept that the procedure described is frequently applied to select a more particular model; and I consider (c) as analogous to eliciting a PDF using data obtained from a number of sources.

D.43 The MASCOT transport model requires PDFs of quantities such as flow velocity at the repository or travel time through a particular section of a hydrogeological unit, from which input values are sampled in the Monte-Carlo analysis. Ideally these would be derived from the multi-dimensional flow model, but because of the highly parameterised nature of NAMMU it is not practicable to use it to make large numbers of calculations across the range of PDFs of the underlying hydrogeological parameters. Nirex therefore uses a 'response surface' technique to extrapolate approximate relationships between the required MASCOT input parameters and key hydrogeological parameters from only a limited number of NAMMU calculations [COR/510, pp.16 right & 17 left, & fig.5]. Calculations are made for a base case, using representative (central) values for parameters, and for a suite of variant cases in which one or more parameters is changed. In the same way that a straight line may be drawn through a scatter of points on a standard X-Y graph so this method then fits a planar surface through the scatter of points on a 3-axis representation of the output data. Whatever the statistical methods used to develop the response surfaces for the required parameters or the degree of departure of computed values from the response surface equivalents, the method does introduce one further step of simplification and room for uncertainty into the overall risk calculations. However I believe the use of such a technique is necessary and appropriate at the present stage of development of the safety assessment modelling.

Calibration, validation and verification of models

D.44 I regard verification as a quality assurance procedure of checking the computer codes to ensure that mathematically they faithfully represent the modelled system, and that the programs are correctly encoded and solved, and run as expected. The process of verification is defined in the Royal Society report [COR/605, p.87] and in a report on Nirex geochemical modelling [FOE/8/38, p.E1]. The latter describes how the particular program HARPHRQ is difficult to solve for anything other than the simplest system so verification has tended to rely on inter-code comparisons, i.e. different programs implementing the same model [ibid.]. The principal groundwater modelling programmes NAMMU and NAPSAC have been in use widely enough and long enough that they are well verified. The probabilistic safety assessment program MASCOT is described by Nirex as having been verified through international code comparison exercises [COR/507, p.6].

D.45 The process of calibration of a model is adjustment of the input parameters until the model sufficiently matches observations, and is usually required because it is not possible to obtain field measurements of all hydrogeological properties at an appropriate scale. A difficulty with calibration, especially with models like NAPSAC and NAMMU which require the input of values for many individual parameters, is that there may be many plausible combinations of parameter values that approximately match a particular set of observations. In seeking to validate the model it would therefore be necessary to consider a range of predictions from the alternative calibrations. Calibration of a broad groundwater model is typically based on obtaining the best fit between simulated and measured heads or, in a coastal case like Sellafield, heads and salinities. The best calibration may fit the available historical data well but prediction may be poor if future stress patterns on the aquifer are different.

D.46 Model development is achieved by using cycles of prediction and testing goodness of fit against collected data. The model is amended and refined and the cycle repeated against new and existing data. The model usually improves and achieves greater resolution with each phase of development but may not necessarily be validated. Validation is the process of demonstrating that a conceptual model and its numerical models and computer codes adequately represent the real world by comparing model predictions with independent field observations and/or experimental measurements. [Similar definitions appear in COR/605, s.5.8; GOV/503, p.6; HMP/1/1, p.8 etc.] A model, calibrated to suit the observational data, can be used to make predictions which can be tested against new data. If the match is not close enough then, by an iterative process, the model must be adjusted and further tested. Validation comes when the predictions match reality, within a defined margin of acceptability appropriate to the purpose, over a wide enough range of observational and test situations. There is no absolute standard for validity: I am therefore not surprised that Nirex prefers to describe the need for its models to be 'fit for purpose'.

D.47 To date, much of the Nirex work on model validation has been generic, demonstrating the suitability of the range of computer models used, rather than specific to assessments of the proposed Sellafield repository. The key element in validation - of prediction followed by comparison against data not previously used - has been particularly difficult for Nirex because, in constructing its basic conceptual geological and hydrogeological model of the Sellafield area, it has already made use of the many pre-existing boreholes and a substantial proportion of its own boreholes. The independent data needed for comparison must therefore come from additional fieldwork but sinking new boreholes and carrying out large scale pump tests is slow and costly because of the depths involved and the quality and precision of equipment and measurement required, so the number of cycles that can be gone through in the rigorous application of validation is limited.

D.48 It appears that the RCF3 pump testing has been the first major prediction and comparison exercise as part of the specific validation of models of the PRZ but in the event it was not possible to follow the ideal procedure of making completely blind predictions whose details were unknown to those conducting the tests until after the event. It was indicated by Nirex that six groundwater flow models were being compared but no results were available for the inquiry. If similar testing could be repeated more widely in more holes this would represent a further opportunity for comparing the models but it is not likely that any would be regarded as validated in advance of construction of the RCF. Indeed Nirex describes the first phase of the RCF science programme as being concerned with validating its hydrogeological, geochemical, geotechnical and radionuclide transport models. On the other hand, the requisite models must be sufficiently developed to credibly predict the disturbance effects of the RCF itself.

Relationship between modelling and baseline conditions

D.49 Baseline conditions are not necessarily static or constant. Near surface water levels, for example, would be expected to rise and fall seasonally and from year to year, and to show greater or lesser responses to natural processes from daily tides to long term climate changes. Moreover present 'baseline' conditions may not represent a state of equilibrium, but may only be a snapshot in an evolving pattern responding to ongoing geological, geomorphological or climatic change or still responding to past changes, as for example the way that the region is still recovering from the effect of ice loading during the last glaciation by continued slow uplift. The deep parts of the system - the low permeability BVG - may still be responding to changes tens of thousands or more years ago [D.25 above] and the groundwater chemistry and irregular environmental pressure heads may reflect conditions distant in time.

D.50 In the present context and for most practical purposes, including predicting the disturbance caused by the RCF itself, I consider that baseline groundwater conditions are represented by the observable average and range of measurements under natural conditions over a period of a few years. Models can never achieve a perfect quantitative match with real observations (although one would expect a close qualitative match) so it is not necessary to know that a system has returned to complete baseline conditions following the effects of intrusion by drilling, sampling and testing. It is more necessary with groundwater chemistry to establish baseline conditions because small variations can significantly alter reactions, the stability of particular chemical species, and equilibria generally.

D.51 It is difficult to validate a model if all there is to compare it against are undisturbed natural, i.e. baseline, conditions. Part of the process of testing and validating models is usually to stress the system away from its natural equilibrium, but this must be done in a controlled and measurable way.

Next steps in model development

D.52 I do not believe there is any geological or hydrogeological aspect that has not been included in some form of modelling to date, if only with scoping studies, but work is needed, and appears to be progressing, on many fronts. The overall conceptual hydrogeological model has remained substantially the same since at least the end of 1993 [COR/517] but needs more detail, the incorporation of more processes, and further calibration to better match the existing groundwater conditions as known from the present body of information. Further data, especially filling gaps in the 3-D picture of the geology and hydrogeology, will undoubtedly necessitate further adjustment. To explain and replicate the salinity distributions and irregular groundwater heads I believe requires more detailed modelling of the geology and the incorporation of more factors affecting flow through fractured rocks.

D.53 The current representations of the system are predominantly two-dimensional steady state simulations and 2-D modelling will continue to be important. I believe there is a need for more 2-D studies, coupled with additional exploration, to investigate both divergent flow away from the PRZ across the Seascale FZ and the influence of the Carboniferous Limestone to the north.

D.54 There are numerous reasons why more emphasis is required on three-dimensional modelling:

(a) There is a need to extend and improve the methodology for numerical modelling of present day hydrogeological conditions and to better represent flow in 3 dimensions on a greater than district-wide basis;

(b) The hydrogeological/geosphere modelling should be capable not only of analysing the performance and risk associated with a specific location of a repository in 3-D space but should be capable of exploring the effects of varying that location in the 3-D volume of the PRZ and beyond. The present emphasis on 2-D modelling along a cross section passing through the PRZ is limiting in this respect;

(c) I consider that the characteristics of the volcanic host rocks and the intensity of significant faulting within and immediately surrounding the PRZ will in any event require a more detailed representation of the 3-D geology and its hydrogeological characteristics to adequately model flow from the vicinity of the proposed RCF;

(d) To cope with scenarios representing future changes of climate, landform, etc it is necessary to consider changes in 3-D groundwater flow patterns. NAMMU and NAPSAC, being highly parameterised models, are not suitable for such a purpose. More broad-brush 3-D numerical models are needed, capable of more rapid testing of alternative scenario conceptual models and sensitivity analyses.

(e) Age dating of groundwater could be a powerful means of calibrating and validating the overall conceptual models but current models are not yet able to explore this very well. Broad-brush 3-D models could be used to investigate the evolution of the groundwater system up to the present as a guide to possible future behaviour.

D.55 Advances are needed in the modelling of groundwater flow, and of radionuclide transport, through fractured rock. Linked to this is improvement in coupled thermo-hydromechanical models. Two-phase flow, involving water and gas through fractured rock, is also not yet capable of being modelled adequately. Much of the work needed to overcome these deficiencies is of a generic nature and is tied up with international research efforts, but once better numerical models have been developed they will still need to be applied and validated in the specific Sellafield host rocks.

D.56 The emphasis to date has been on steady state modelling but more transient models are required to cater for long term climatic, geological and other processes.

D.57 There is a need to model in more detail the effects of the construction and operational phases of the proposed RCF on groundwater conditions and also how the RCF might affect the post-closure performance and risk of an adjacent repository. The only study submitted to the inquiry, Nirex report 560 [FOE/5/19], looks distinctly out of date.

D.58 Conditions and processes going on at depths well below the proposed repository could have an influence on groundwater flow and geochemical conditions relevant to repository performance but do not yet appear to have been given much attention in numerical modelling, and indeed there is little data against which to compare at these depths. Such matters are likely to have to be addressed in due course.

D.59 Modelling requires data, and validation of models requires fresh data. There is a need to reduce uncertainties in the data available for detailed PCPAs - to narrow the PDFs of MASCOT input parameters and rely less on elicitation - which points to the need for much more site data, and at a wider range of scales to assist with upscaling.

E RADIOLOGICAL PROTECTION & SAFETY ASSESSMENT

The multi-barrier concept and its stages of protection

E.1 A DWR at Sellafield is intended to rely on a multi-barrier concept to protect future human populations from harmful radiological effects, firstly the physical and chemical barriers in the engineered repository, then the ameliorating effects on radionuclide transport of the geosphere and eventually the biosphere. The initial, physical barrier would be provided by the containers and grouts in which the waste materials are packaged. These would be surrounded by a chemical, and to some extent physical, barrier consisting of the porous cement-based vault backfill (NRVB). Then there is the thickness of the overlying and surrounding rocks with their particular geochemistry and hydrogeology, and finally the effects of the dispersion and redistribution of radionuclides in the soils, sediments, water and air comprising the biosphere.

E.2 With conventional waste disposal the usual method of containment is to limit the throughflow of water and the production and escape of leachate by lining and capping the wastes with low permeability materials and by allowing the controlled venting of gases to the atmosphere. Clearly this is not possible with a deep radioactive waste repository surrounded by saturated rocks. Given the very long half lives of some radionuclides, the critical function of the engineered barriers is to retard rather than absolutely contain.

E.3 An important factor is the need to avoid a build-up of gas, which has lead to the need for the vault backfill to be gas-permeable and to preliminary designs for a proportion of the containers to be vented. But the consequence is that groundwater will be able to penetrate and pass through the wastes, which in turn leads to the need for additional chemical containment and reliance on the corrosion of iron to produce anaerobic, low-Eh repository porewater conditions and the slow dissolution of NRVB to maintain high pH. In contrast to conventional means of predominantly physical containment such as the use of bentonite clay lining layers, the permeable chemical barrier of specially formulated NRVB is an untried material and its application an untried concept.

E.4 A feature of the engineered repository as currently proposed is the intention to have a continuous crown space above the emplaced waste. (Until 1993 at least, the intention appears to have been to fully backfill the vaults [COR/505, fig.1].) The void has the drawback that it would represent a short circuit for groundwater flow from the upstream to the downstream end of each vault. However Nirex claims that diffusion of dissolved radionuclides from the backfilled waste into the crown space can slow down the releases compared with models that assume the vaults are fully filled with well mixed waste. In MASCOT it is assumed that, away from intersections with Type II features, crown flows are layered, with decreasing radionuclide concentrations upward [COR/522, v.3, s.3.2.3], although the rate of flow would affect the degree of mixing, which is principally by diffusion, and is allowed for in the modelling [COR/528, p.21 Box G]. Whether the water is layered or vertically mixed it seems to me that the principal advantage of a vault crown space is that there will be homogenisation along the length of crown space of waters from different sources: any leachate from the wastes will become blended with water conditioned by contact with NRVB and the inflowing groundwater. It seems to me that more work has to be done to show that the system as proposed would be better in terms of overall fluxes and radionuclide concentrations than if the void is fully grouted and/or the vaults are divided into shorter self-contained lengths by means of dams.

E.5 For the purposes of the Nirex 95 preliminary safety assessment, post closure physical containment was assumed to be zero for the base case, or 1000 years for a variant probabilistic case [COR/522, v.3, s.3.3.1(a) & 6.4(b)]. Clearly the longer that radionuclides can be retarded in the repository the greater will be the decay of shorter-lived elements even before they might escape into the geosphere. Nirex hopes to achieve physical containment for at least one thousand years, during which period it estimates around 99% of the radioactivity would decay. This is a clear illustration of the important contribution that the engineered barriers could make to improving the safety case. The function of the chemical barrier is to retard longer lived radionuclides, and Nirex estimates that if it is effective for 1 million years then around 99% of all those remaining would also decay within the repository.

E.6 Some of the uncertainties and difficulties regarding solubility, sorption, pH, Eh, etcetera, have been referred to in sections 6C and D. Whilst assumptions of post closure physical containment of zero or 1000 years may well be very conservative, the assumptions that organic degradation products (believed to increase the solubility of some radionuclides) will be uniformly distributed throughout the repository, and that the PDFs that characterise sorption coefficients and solubility limits in MASCOT remain fixed over the entire period of repository evolution [COR/522, v.3, s.3.3.1] are obviously great simplifications and may be non-conservative.

E.7 It seems to me that one of the advantages of a multi-barrier system, such as that envisaged at Sellafield, is that the engineered elements could if necessary be varied locally or more generally so as to achieve differing degrees of waste containment, or to modify and improve on near-field radiological performance and hence that of the system as a whole. There is scope for alternative methods of pre-processing and encapsulation of the waste, use of special containers, varying the formulation and quantities of backfill surrounding the containers, alternative vault geometries and layout, and so on. For modest volumes of selected wastes it may be possible to achieve a high degree of physical containment.

E.8 In the case of the agricultural wells exposure pathway, which has produced the greatest base-case risk in the Nirex 95 calculations [see E.58 below], the largest contributor to risk is ^{129}I, but Nirex argues that there is scope for special engineered measures to better contain its very limited volume [COR/522, v.3, p.6.20]. Assuming it is practicable to separate out iodine-bearing waste - Nirex suggested 50% may be possible - it seems to me reasonable for Nirex to do so. Although it might be thought of as placing extra reliance on the engineered barriers, I would regard it as good engineering practice and the adoption of best practicable means.

E.9 The need for artificial barriers might be regarded as surprising when the philosophy behind deep waste disposal is to be able to rely on the geosphere as the primary barrier. A requirement for geological disposal implies a need for the natural strata to play a primary role in confining and retarding harmful constituents of the wastes, and the emphasis on deep burial is to increase isolation and minimise risks from intrusion and disruptive external events, natural or otherwise. However I perceive a shift in international guidelines [as described in A.8] to give greater weight to the artificial barriers in a multi-barrier system and to recognise dilution as a geosphere process that might reduce risk [A.16].

E.10 As for the host rocks surrounding the repository, an optimum location would act both as a physical and chemical barrier to the return of radionuclides to the biosphere. There the rocks would restrict groundwater flow and cause long, slow, predominantly downward flowpaths, and have geochemical characteristics that inhibit radionuclide solubility and encourage precipitation, mineralisation and other sorptive processes. However I have already commented that the regional setting is such that the expected flowpaths at Sellafield cannot be regarded as long by comparison with ideal environments [para.B.32], and the Nirex 95 modelling described below shows that predicted flowpaths away from the repository are predominantly upward in the BVG host rocks. Moreover the travel times for water flow through the volcanic host rocks may be much shorter than through the overlying sedimentary formations [eg COR/522, v.3, table 2.3]. I have also referred to various aspects of the geology and hydrogeology of the Sellafield district that could be important but for which there is much uncertainty, including the structure and stratigraphy, the flow characteristics and conductivity of the rocks, and sorption processes [C.70-98].

E.11 Nirex regards it as an important part of the safety case that any radionuclides dissolved in groundwater emerging from the BVG would be diluted by much higher flow of water in the overlying rocks and a positive advantage of the Sellafield location that for most climate states the discharge will be predominantly marine [COR/522, v.3, s.6.3 last para. & 6.4(a) first 2 paras.]. The degree of dilution in passing through the rocks to the discharge location is estimated at anything from 4 to 100,000 for a steady-state case (the wide range being indicative of parameter uncertainties) but the best estimate for a transient flushing out of radionuclides such as ^{36}Cl, which determine peak risks in the first million years, is a dilution of around 2000 [ibid., s.2.3 p.2.13]. Various opposing parties object to the principle that there might be a discharge of polluted groundwater to the sea but marine dilution would undoubtedly reduce the risks to the human population: Nirex calculates the risks as about three orders of magnitude lower for marine discharge than terrestrial [ibid., 6.4(a) 1st para. & fig.6.6]. This would be relevant to climate states similar to that of the present or warmer, when sea levels are relatively high, but not to colder climate states that result in lowered sea levels and 'terrestrial' conditions.

E.12 Of course radionuclides that reach the biosphere in groundwater, and perhaps gas flows, may not only become widely dispersed in water and soil but may be re-concentrated. Sediment particles of a particular size or density in or on which radionuclides have become attached may be preferentially segregated and the radioactivity concentrated, as with beach or estuarine sediments, or the muds on the sea bed west of the Isle of Man [IRL/1/1, Map 2]. Similarly radioelements may become preferentially taken up by particular crops, or in marine creatures, or by other means concentrated in the food chain, though Nirex has submitted detailed calculations to show, for example, that although radio-iodine (^{129}I) can be concentrated in seaweed even people who eat the weed as laverbread would receive only an insignificant dose [NRX/15/34].

E.13 The multi-barrier approach may appear 'belt and braces'. Some elements have a sound pedigree but, taken in the round, it is novel and unproven. The construction, maintenance and subsequent closure and sealing of repository vaults, access shafts or drifts, and of RCF galleries and shafts, are essentially mining and civil engineering operations, for which there is a wealth of experience, expertise and available technology. I believe this extends to the sealing and restoration of shafts and openings: whilst much higher standards need to be achieved than in normal mining practice, and methods will need to be tested on site [C.101], in general I consider that appropriate materials and techniques are already available [F.91]. However the principal elements of the barrier system are unproven and uncertain: the vault backfill and its special chemical buffering and containment is new and untried; saturated, fractured, volcanic rocks such as the potential BVG host rocks have not previously been studied in detail for their geological, hydrogeological and geochemical characteristics; the location is coastal, in a latitude subject to major climate changes including glaciations and consequential large changes in sea levels; and it is also in a zone where the degree of tectonic stability is open to question [C.125]. All these factors make the task of demonstrating the effectiveness of the system a difficult one.

Models, Qualitative Analyses and Multiple Lines of Reasoning in Safety Assessment

E.14 The objective of a detailed safety assessment submitted to regulators would obviously be to express in as quantitative terms as possible the behaviour and evolution of a repository and its environment and consequential radiological risks to human populations into the distant future. First and foremost therefore, the risk assessment would be expected to make use of numerical models of the behaviour of the system, devised, developed and implemented as discussed in section 6D above. However the White paper [GOV/208, para.78], in setting a risk target for design rather than a specific limit, recognises that the nature of a geological disposal system makes it less amenable to quantified risk assessments than say a nuclear reactor, so that whilst calculations of risk can inform a judgment, other technical factors, including ones of a more qualitative nature, will also need to be considered. HMIP has in mind performance and other safety indicators such as radiation dose, radionuclide flux, time, environmental concentration and radiotoxicity, as suggested by the IAEA [HMP/1/1, paras.8.20 & 9.5].

E.15 Qualitative methods of analysis are appropriate, firstly because of the long timescales under consideration, and secondly because of the nature of some of the risks. As for timescale, HMIP rightly observes that the relative importance of quantitative and qualitative arguments will change as uncertainties increase with the evolution of the disposal system over time [HMP/1/1, para.9.2], so it is expected that at times longer than those for which conditions can be modelled, scoping calculations or qualitative arguments may be used [HMP/1/1, paras.6.14 & 8.23]. I discuss the relevance of time periods below [paras. E.71ff].

E.16 As for the second reason, some circumstances that may give rise to risk are not amenable to rigorous modelling, or there may not yet be adequate understanding of the processes involved to construct numerical models, or the probabilities or consequences may be so low that a detailed assessment is not justified. In these circumstances scoping studies and judgment based on qualitative assessment are appropriate. This has to date been the approach to assessing the risk of migrating gases reaching the surface and the probability of there being human habitation or installations where gas could accumulate, and its potential consequences [COR/605, s.9.3], and seems to have been the approach to assessing the low risk of future human intrusion or of natural catastrophic intrusion. For more foreseeable possibilities of human intrusion it is intended to make quantitative risk assessments based on a range of devised intrusion scenarios [NRX/15/2, p.4 top], and for the effects of natural catastrophic events an emphasis will be placed on studies of analogue events [ibid., p.19 lower left].

E.17 The draft regulatory guidelines envisage the application of 'multiple and complementary lines of reasoning' in making a repository safety case [HMP/1/1, para.9.5]. This would include consideration of performance and safety indicators other than direct expressions of risk [see E.14 above]. I would expect this approach also to address issues such as geologically long term processes that could influence groundwater movement but which are not amenable to numerical modelling, including uplift and erosion, evolution of the Irish Sea basin, mineralisation episodes and tectonics. Another circumstance where multiple lines of reasoning would be appropriate is where alternative but plausible conceptual models or computational methods could be applied in assessing a part of the system, or even the system as a whole [see para.D.41 above]. Nirex has arrived at what is essentially a single overall conceptual hydrogeological model but in due course it will be necessary for the developer to show whether other conceptual models are plausible and could explain all or parts of the system. It would also be appropriate for a detailed safety assessment submission to describe what alternative models and methods have been considered and rejected, and why.

E.18 Even in the most quantifiable circumstances of assessment, a single expression of risk does not convey the whole picture: I would expect there to be presentation of evidence concerning the scatter of values in probabilistic calculations, and what degree of variation, such as the 95-percentile, might reasonably be taken as representing a worst case. Moreover the regulators' draft guidelines [HMP/1/1, para.9.2] note that the expression of just a single value of risk does not convey the implications of the assumptions and logic which underpin it, so the contribution which a risk assessment makes to the safety case for a disposal facility needs to be judged at least as much by its assumptions and logical structure as by the results it delivers.

The Nirex 95 Preliminary Safety Assessment

E.19 The potential performance of a deep repository at Sellafield in respect of the groundwater pathway was evaluated in the 'Nirex 95' programme of work and report [COR/522]. The work is described by Nirex as being a preliminary analysis which, whilst not a comprehensive safety assessment, seeks to explore the impact on the risk of identified uncertainties in the hydrogeological conceptual model, in order to develop understanding of the groundwater flow and repository system [ibid., Preface, 2nd & last paras.]. It was based on the company's understanding of the site as at early 1994. Considerably more data have, of course, been acquired since then and the geological interpretation has been revised in detail.

E.20 I consider that Nirex has been generally following the methodology recommended in 1992 by NRPB [NRX/15/3 (2nd doc. - Recommendations for the practical application of the Board's Statement on Radiological Protection Objectives)]. NRPB identifies 'uncertainty' as the overriding problem in solid waste disposal assessment and notes that it is not possible, even in principle, to model every possible future sequence of events, so formulations have to be developed for disposal assessments [ibid., para.42]. It identifies three categories of uncertainty: conceptual uncertainty arising from the choice of which conceptual model best represents the disposal facility, modelling uncertainty arising from the use of the chosen mathematical model, and parameter uncertainty arising from the choice of parameter values for use in the models [ibid., para.43]. It recommends a staged approach to risk calculations to address these aspects systematically, and suggests:

(i) Sensitivity analyses, in which conceptual and modelling uncertainty could be addressed by using, for example, alternative models, bounding and scoping studies, laboratory and field studies, and natural analogues;

(ii) Scenario selection, whereby uncertainty as to the future evolution of the site could be addressed by selecting a range of scenarios to represent qualitatively different possible futures;

(iii) 'Central value' calculation for each scenario, in which each parameter, including the probability of the scenario, is assigned a central value, and a single calculation is performed to give the central value risk for that scenario;

(iv) Uncertainty analysis, to determine the confidence in the results for each scenario, by assigning PDFs of values for all uncertain parameters, then making large numbers of calculations by sampling parameter values from the PDFs. The results will generate PDFs of possible outcomes (dose or risks) for each scenario [ibid., para.47].

E.21 The study used the MASCOT program and its submodels for source-term, geosphere and biosphere [described in D.30ff] to calculate radionuclide fluxes to the human environment, from which risk to members of critical groups [as defined by NRPB and discussed in E.59] could be calculated and compared against the 10^{-6}/year design target. A range of assessment models has been used but as the values of parameters are in general uncertain the main approach has been that of a probabilistic safety assessment (PSA) relying heavily on elicited PDFs. Deterministic calculations, with fixed permutations of parameters, were made to explore the influence of individual parameters.

E.22 <u>Geological assumptions</u>: The regional flow models used are mainly 2 dimensional but Nirex considers the approximation involved in thus representing 3-D flow is much smaller than current uncertainties in other parameters [COR/522, v.3, s.2.1]. Porous medium flow calculations fed into MASCOT were for a 16km long dog-legged vertical cross section [ibid., v.3, fig.7.1] chosen by an elicitation process to be a reasonable representation of a typical groundwater flow line through the PRZ [ibid., s.2.1.1]. The section does not appear to pass directly through any of the boreholes so data for the nearest few boreholes have been projected onto the line of section. The base of the section, and corresponding models [ibid., figs.2.2 & 2.3], is 3.5km bOD, much deeper than direct drilling results. Even geophysical data would give only a broad indication of geological structure at such depths.

E.23 The cross section intersects a number of major fault zones, and within these and elsewhere there may be some flow out of the plane of the cross section. Only three of the many faults present in and around the PRZ were modelled deterministically, as Type III features; the rest were represented stochastically as Type II features. It appears to me that assumptions about the location and basic properties of the faults make a greater difference to flowpaths and flow rates than the number of faults.

E.24 In each of the Nirex 95 models, the location and dimensions of the notional repository has remained fixed on the 2-D cross section. The effects of shafts and drifts connecting a potential repository to the surface were not modelled as it was assumed that the engineered pathways are adequately sealed and are not preferential pathways for radionuclide escape [COR/522, v.3, p1.2].

E.25 Effective large scale hydraulic properties for the 14 major hydrogeological units incorporated in the hydrogeological conceptual model, and for dispersion and rock-matrix diffusion, were derived by a mixture of inference, elicitation, upscaling from core measurements and experimental data, borehole environmental pressure measurements, and by calculation using mostly continuum porous medium (CPM) modelling [as described in COR/522, v.2, s.5 for the individual units and summarised in s.6].

E.26 The Deep BVG was modelled as a nearly isotropic, homogeneous, fractured rock with flow predominantly in the fractures whose regional scale effective parameters were deduced, with the aid of fracture network models, from borehole environmental pressure measurements [ibid., v.2, s.5.1, 5.1.4 & 5.1.5]. It was somewhat arbitrarily divided into a 'more permeable' upper (Top) and a 'less permeable' Lower part, the division being 400m below the top of the deep BVG, corresponding quite well with the boundary between the Brown Bank and Bleawath Formations in the PRZ [ibid., v.1, s.5.2 & v.2, s.5.1.1]. Type III faults were modelled as discussed in para.D.23 above; Type II transmissive features in the immediate vicinity of the repository were represented explicitly, not as the actual irregular features but as a regular lattice having the same average orientation and spacing and effective permeability [ibid., s.5.1.7].

E.27 The base case assumed that Deep BVG rock properties extended to the base of the modelled cross sections even though the Borrowdale Volcanics are underlain by the Latterbarrow Sandstone and Skiddaw Slates in the locality [COR/522, v.1, figs.4.4a & 4.4b]. Although a variant model allowed for a geological unit with enhanced permeability at depth, identified by Nirex as broadly equivalent to the Latterbarrow Sandstone, FOE say that the sandstone should have been separately modelled from the outset on the grounds that it is 400m thick, and described in the 1937 Geological Survey district memoir as a medium-grained sandstone without mudstone bands and therefore likely have higher permeability and be well fractured. Considerably more borehole data would be needed to show whether the sandstone's characteristics at depth are similar to those at outcrop, but FOE's arguments are not unreasonable.

E.28 As for the other modelled hydrogeological units [shown diagrammatically on COR/522, v.2, fig.5.3], the Near-Surface BVG (in the outcrop areas) was considered as a nearly isotropic, heterogeneous, rock with predominant fracture flow [ibid., v.2, s.5.2]; and the Carboniferous Limestone as fractured and heterogeneous and containing sometimes sizeable, though not extensively interconnected, dissolution features analogous to Type II features, [v.2, s.5.3]. The Brockram was considered as having flow through a heterogeneous, generally sandy matrix and through a network of Type II features [s.5.4], and the St Bees Shale and St Bees Evaporites were modelled as heterogeneous strata of low effective porosity in which flow occurs predominantly in Type I fractures [v.2, s.5.5]. In earlier studies, the Brockram was considered as a low permeability formation, being lumped with the St Bees Shales and Evaporites [FOE/5/19, p.A35] but FOE, reasonably, express surprise, pointing out that the 1937 Geological Survey memoir for the district describes water flow through vertical joints in the Brockram.

E.29 The St Bees Sandstone was subdivided. In the Basal Deep division silty/shaly layers of lower permeability were considered important and the rock was treated as fractured, containing a network of Type II features. The Top of the Deep St Bees Sandstone was modelled with flow through the layered matrix; and the Near-Surface St Bees Sandstone with flows predominantly in Major Bedding-Plane Features [COR/522, v.2, s.5.6]. The overlying Calder Sandstone was divided into a Deep unit, considered to have flow through a heterogeneous and mildly anisotropic matrix [ibid., s.5.7], and Near-Surface unit with most flow along Major Bedding-Plane Features [s.5.8]. As no direct data were available for the Mercia Mudstone, present offshore, all values were elicited, those adopted being similar to the Brockram [s.5.9]. The Terrestrial Quaternary Deposits of the district are highly heterogeneous, from gravels to clays, so the expressed average properties are very speculative; the Marine Quaternary Deposits were considered to be more homogeneous [s.5.10 & 11].

E.30 It seems to me that the general characterisation and manner in which the various geological units have been modelled does reflect the underlying geological nature of those particular stratigraphic units, the major uncertainty being the nature of the fracture systems, fracture flow and connectivity. Nirex contends that the Nirex 95 analysis specifically takes into account what the objectors call 'negative features' by incorporating Types II and III flowing features that could give hydraulic connection over extended distances within the BVG and between the BVG and overlying sandstones; by assuming that the Brockram is capable of significant flows; and assuming the Basal Deep St Bees Sandstone contains cross-cutting transmissive features. However the model construction obviously simplifies the geology, to the point of eliminating the Latterbarrow Sandstone and Skiddaw Slates by assigning to them identical properties to the deep BVG, and variant models which incorporated a distinctive hydrogeological unit at about the depth of the Latterbarrow Sandstone or which imposed defined heads and salinities along the bottom boundary of the model achieved a better representation of actual groundwater heads than the base case [E.38 & 39 below]. This indicates that the geology and processes at depths well below the preferred repository range may be very influential and need to be better represented in models.

Deterministic calculations

E.31 For each of the principal climate states, central-case deterministic (MASCOT) calculations were made to explore the processes determining the magnitudes and timings of significant risk contributions. These made use of 'central' (peak or median) values of the PDFs [COR/522, v.3, s.6.5]. The deterministic calculations for the Boreal terrestrial state [ibid., fig.6.13] can be compared with the probabilistic [fig.6.8]. As previously discussed [para.D.40], probabilistic calculations tend to flatten the mean risk curves.

E.32 In relation to the source-term sub-models, I agree with FOE that it was rather non-systematic to assume post-closure physical containment of radionuclides as zero for the base case but 1000 years for a variant [para. E.5 above]. There is no extended practical experience of the durability and effectiveness of the specific man-made repository containment materials so the value adopted for the containment period in a deterministic calculation is arbitrary. However both zero and 1000 years seem to me to be probably conservative in relation to what I suppose to be possible using existing technologies, and the findings of natural analogue studies on, for example, metals, concretes, bentonite clay and bitumen are encouraging [GOV/630, Chap.4].

E.33 Also in relation to the behaviour of the repository near field, calculations were made of fluxes over time of important radionuclides (^{36}Cl & ^{238}U series) from different sections of the vaults - midstream, downstream and intersection (and an upstream section adopted for other purposes). Because of the great length of the vaults, flowing groundwater would take distinctly different paths away from the different sections so it is appropriate that the modelling should consider such subdivisions. The 'intersection' zones reflect the external geological influence of Type II flowing features where they have been cut through by the vault excavations. As might be expected where flow is concentrated, the radionuclides in wastes in the intersection zones were depleted first [ibid., v.3, s.6.5(b)].

E.34 Parameter sensitivity studies were carried out by Nirex on the deterministic model to examine the effects of varying groundwater flux through the repository [ibid., v.3, s.6.6(a) & fig.6.17] and varying the longitudinal dispersion factor in the geosphere [ibid. & fig.6.18]. The former showed that higher flows did not greatly affect the early (^{36}Cl) risk, perhaps because of the relatively short travel time through the BVG, but the later (^{226}Ra) peak was considerably increased and arrived significantly sooner. However decreased flow was found to reduce the early risk, showing that the source-term becomes more dominant at lower flows.

As for dispersion length, this was found to have little effect on the magnitude of risk, and other analysis shows that travel time in the geosphere is more important [ibid., p.6.16].

E.35 Variant calculations from the base case were made as a means of developing 'response surfaces' which are used to simplify MASCOT calculations [see para. D.42 above]. This was done mostly by increasing one parameter at a time by 10% for parameters expected to most affect flux through the repository or groundwater travel times [COR/522, v.3, s.2.4.2]. 10% variation seems very small in relation to the uncertainty and total variability surrounding these parameters but Nirex expresses confidence that response surfaces constructed from 10% variants acceptably represent the system.

E.36 In applying these values in MASCOT probabilistic realisations, the response surfaces allow flux to be calculated in proportion to the permeability or transmissivity of the flowing features but the flow path lengths were kept fixed at base case values on the grounds that their uncertainties were much smaller than those of fluxes and travel times [ibid., p.2.16]. This introduces one further approximation into the overall calculations. The greatest uncertainties in travel times appear to be associated with BVG matrix porosity and Types 0 and I features, Top Deep St Bees Sandstone bedding features and Type III transverse features, and Near Surface Calder Sandstone bedding features [ibid., Table 2.6].

E.37 <u>Variant cases</u>: Calculations were made to address issues not addressed by the recommended base-case model. In particular discrepancies between calculated heads and salinities and those actually observed [as described in C.43 & C.52 above] were explored in a number of variant calculations. The resulting calculations of groundwater flow and salinity transport were then used in deterministic MASCOT calculations to estimate risks [COR/522, v.3, s.1.5]. As there are considerable observed heterogeneities within and between even nearby boreholes, and as the base case models gave a relatively poor match, I would not have expected any single variant model to give a close match with the observational data.

E.38 A notable shortcoming in the base-case model is that it does not match the significant increase in observed heads with depth in the vicinity of the PRZ. The cause of these high heads is not known but a model was created with the distribution of salinity approximating to that observed [ibid., fig.7.13] and high heads imposed on the bottom boundary. Attempts to model actual salinity distributions produced locally physically unrealistic flow velocities, particularly in areas close to highly transmissive regions [COR/522, v.3, s.3.2]. As noted by objectors, the imposition of observational data to produce a better fit does not improve understanding of the model. This 'Imposed High Heads & Imposed Salinity Distribution' variant has the effect of significantly reducing the travel time in the sandstones but not greatly changing groundwater flux through the repository [ibid., table 7.1]. It produces very shallow flow pathlines in the upper sandstones [ibid., s.7.3]. For the Boreal Terrestrial case, the peak risk was increased 2½-fold and brought forward in time.

E.39 The 'Transmissive Feature at Depth Variant' assumes there is a rock unit in the BVG below repository depth of enhanced hydraulic conductivity and in hydraulic connection with high groundwater heads in the higher ground inland. For the purpose of the exercise it was assumed that the Latterbarrow Sandstone between the LDBFZ and the FHFZ is more transmissive than the surrounding rock [ibid., s.7.4]. There are no observational data to support this proposition but I suppose it to be a reasonable possibility [see E.27 above]. On the diagram of this variant [ibid., fig.7.16], the transmissive unit is absent beyond the FHFZ. However, even if it had been modelled west of the fault zone, I do not believe it would have made any significant difference to the outcome: the magnitude of the fault is such that hydraulic continuity within the unit across the fault zone is unlikely, and the dip of the rocks and proximity to the brine mass west of the fault zone are likely to more dominant factors. In the opposite direction, the diagram does not extend far enough to show whether the Latterbarrow Sandstone is modelled as continuing eastward in hydraulic continuity all the way to its outcrop beyond the LDBFZ but this also does not appear to matter: the fluctuations in BVG heads in Boreholes 8/8A west of the LDBFZ show that this is in a recharge zone, and the model appears to be consistent with this.

E.40 This variant gave a better match between calculated and observed densities and environmental heads but was still not good. In fact the Imposed High Heads variant and Transmissive Feature variant give virtually identical peak risks [COR/522, v.3, table 7.7] and time/risk curves that appear to be completely alike [ibid., figs.7.23 & 7.24]. (The latter I find surprising as I would have expected some differences to result from two quite different sets of assumptions).

E.41 Two sets of variant calculations were made to explore the influence of the Seascale FZ. The first variant - 'Flow within the Seascale Fault Zone' - was devised because the line of cross section cuts the fault obliquely and there is a possibility of significant groundwater flow within the fault zone out of the plane of the 2-D section. To approximate this, the fault halo width was increased [ibid., fig.7.17]. The effect was to make pathlines deeper but to shorten travel times in most hydrogeological units [ibid., s.7.5]. The second variant - 'Seascale Fault Zone not a Type III Feature' - assumed the fault zone has properties the same as the background rock. This was found to better match observed salinities and heads but pathlines downstream of the SFZ are shallower than the base case and result in reduced travel times [ibid., s.7.6]. For the Boreal Terrestrial example, both variants increased the peak risk and brought forward its occurrence compared with the base case [ibid., table 7.7].

E.42 A variant model explored a 'Less-dense Network of Type II Features in the BVG'. It is expected that there will be several intersections of Type II features with each vault and these would significantly affect through-flow of water. [COR/522, v.3, s.1.3] The density of the lattice of Type II features was halved and the implicit effective properties in the BVG recalculated using NAPSAC. The effect was to reduce mean flux through the repository, typically by two-thirds, but overall pathlines and travel times stayed similar to the base case [ibid., s.7.7]. The calculated peak risk reduced by a little over one-third and was slightly later compared with the base case [ibid., table 7.7]. Objectors have suggested that a variant with a reduced density of major flowing features should be matched with one with an increased density, which Nirex agrees would give increased flow through the repository though not greatly change flow paths because the Type II features dominate the flow. However I note that in the base case the average fraction of vault length occupied by intersections with Type II features was about 0.44 [ibid., v.3, s.6.1.4] which already seems quite high. If RCF galleries are excavated and actual examples of Type II features are recognised and mapped then it may well be appropriate to explore the effect of higher or lower densities in deterministic calculations as well as allow for such variation in probabilistic calculations.

E.43 A further variant assumed the 'Basal Deep St Bees Sandstone a Barrier to Flow'. This was tried because Nirex was encouraged by preliminary results from the RCF3 pump test, although I consider that the results are now less clear [see C.84-87]. The hydraulic conductivity of the unit was reduced by about 1½ orders of magnitude, the effect of which was to make pathlines a little deeper and travel times a little longer [COR/522, v.3, s.7.8], with a corresponding small lowering and delaying of peak risk [ibid., table 7.7].

E.44 Nirex considers the difference between peak risks calculated for the different variants to be relatively small and sees it as important that the calculated risk for the base case is not too far from that for the variant with imposed high heads [ibid., v.3, p.7.10]. The Boreal Terrestrial biosphere examples [ibid., table 7.7 & figs.7.23 to 7.28] ranged from about $5.5x10^{-7}$ at 2,000 years post-closure (Transmissive feature at depth & Imposed high heads/imposed salinity cases) to about $1x10^{-7}$ at 25,000 years (Reduced density of Type II features case). Thus in these deterministic examples, those that appeared to give the better match with site observations, including the imposed high heads case, produced risk estimates about 2½ times greater than that for the base case of about $2x10^{-7}$ (at 20,000 years). However Nirex says that these variants, with reduced geosphere spreading time, should actually be calculated to give risks similar to the base-case because it argues that a different shape of source-term release pulse should be applied [ibid., v.3, para. over p.8.11/12]. I would not regard differences of 2½ times between deterministic models as being as slight as implied by Nirex, especially if the peak risks are well within an order of magnitude of the design target.

E.45 The variant models explored in a fairly simple and coarse way some of the geological and hydrogeological features that exert a physical control on the behaviour of the system. It would have been possible to try more variants, for example with quite different properties for the Brockram or the Fleming Hall Fault Zone, or to try combinations of variant features, such as a Transmissive feature at depth and Seascale Fault Zone not a Type III Feature. Some of the variant models improved the fit between calculated outputs and field observations, as expressed in terms of heads and salinities, and in due course, if it can be shown that the variant features more closely represent reality, then they would appropriately be included in revised conceptual models. Modelling has not yet reached the stage where variant calculations could be made to explore thermal effects (from the repository or geothermal), or variable permeability of units within the BVG.

Probabilistic calculations

E.46 Probabilistic risk calculations were made for 'realisations', each with a set of parameter values obtained by random sampling from specified PDFs. Doses were calculated as a function of time, for individual radionuclides and in total, for each biosphere model, then converted to risk. Base case probabilistic calculations for each climate state contained 500 sampled realisations, but the results are mostly presented as mean risk against time, up to 10^8 years after closure. However the scatter of risk associated with the many realisations can be expressed for any moment in time post-closure, as in the examples COR/522, v.3, figs.6.9 & 6.10. These show that a few percent of the realisations for the Boreal terrestrial geosphere at 1 million years exceed the 10^{-6} risk target.

E.47 Fig.6.6 [ibid.] presents curves of risk (i.e. the mean risk for many realisations) plotted against time for each of four climate states, and table 6.18 summarises the timing and magnitude of the peaks in these curves. (Although the possibility of a 'Mediterranean' climate is predicted under the effects of greenhouse gas warming [see para.C.133], calculations have not been presented for this climate state.) The models show that at times beyond about 1 million years the most important radionuclide is always ^{226}Ra (derived from ^{238}U) and at earlier times ^{36}Cl is by far the most important. Under most climate states, the predicted early peak of risk comes at about 20,000 years and the late peak at about 4 million years.

E.48 Prior to the Nirex 95 report [COR/522] published in July 1995 there was the Nirex PSA Overview report [COR/507] of October 1994, and a little earlier still Nirex Report 560 [FOE/5/19] of February 1994. The examples of modelled output of risk with time presented in these reports suggest to me that a rapid evolution has been taking place in what constitute base-case models. There is a notable difference between what I suppose to be comparable graphs of probabilistic steady state runs for the three principal climate states, i.e. COR/522, v.3, fig.6.6 & COR/507, fig.5; or between graphs showing contributions from individual radionuclides for the Boreal Terrestrial model, i.e. COR/522, v.3, fig.6.8 & COR/507, fig.6, and FOE/5/19, fig.3.6 which I believe to be a similar case.

E.49 The differences appear to be the result of a combination of numerous changes, including the incorporation of more components into sub-models, revised assumptions about the repository and the wastes, amended properties of hydrogeological units, and so on. The basic modelled cross section is the same and the biosphere modelling and factors appear to have remained similar but the source-term calculations have moved from simple vault sections to more detailed sub-models [FOE/5/19, s.B2.1.1 compared with COR/522, v.3, fig.3.3 (explained in s.3.3.1(b))]. The number of geosphere hydrogeological units has been increased, eg where previously the St Bees Shales & Evaporites and Brockram were treated as one and the sandstones had just two divisions [FOE/5/19, table A7 & COR/507, fig.3] in Nirex 95 these are represented by 7 subdivisions [COR/522, v.2, fig.5.3]. In consequence the flowpaths through the geosphere modelled in MASCOT have become more involved, from Report 560 [FOE/5/19, fig.3.1 (MASCOT) & fig.A12 (the underlying NAMMU model), explained in s.B2.2.2] and the Overview report [COR/507, fig.3, a simplified version of the FOE/5/19, fig.A12] to Nirex 95 [COR/522, v.3, fig.4.1 (which omits units in which travel times are short)]. Other examples of changes are in the PDFs of hydraulic conductivity for the various hydrogeological units [FOE/5/19, fig.A24(a) (m/s conductivity); cf. COR/522, v.3, fig.5.1 (m^2 permeability - see bottom bar for conversion)] and of effective porosity [FOE/5/19, fig.A24(b); cf. COR/522, v.3, fig.5.2]; revised assumptions about the radionuclide inventory [FOE/5/19, table B9; cf. COR/522, v.3, table 6.2]; changes in near-field solubility limits and sorption distribution coefficients for some elements [FOE/5/19, tables B13 & B14; cf. COR/522, v.3, tables 6.6 & 6.7 central values], and the multipliers to allow for the presence of organic compound [tables B16(a/b) & 6.9(a/b) respectively], and in some far-field (BVG) sorption distribution coefficients [table B17(a) cf. table 6.12].

E.50 <u>Parameter sensitivity studies</u>: Nirex has carried out sensitivity analyses to explore the importance of individual model parameters. One method was to plot the output value of risk against a particular input parameter for each of many probabilistic realisations to look for any correlation between the two and any effect of the parameter on performance [COR/507, fig.7 & p.15]. The relevant data are not illustrated in the Nirex 95 report but Nirex says the largest sensitivity is to the ^{36}Cl inventory, and a weaker effect is the value of groundwater flux in intersection and midstream vault-section source term submodels. Risk does not appear sensitive to individual parameters when taken one by one [COR/522, v.3, s.6.6(b)].

E.51 Variant probabilistic calculations were made for simplified versions of the system model, to identify the contribution of different system components to the overall performance, eg calculations in which all groundwater flow was directed through one of three paths through the repository and BVG (downstream, midstream and intersections) showed little difference in the magnitude and timing of both the early (^{36}Cl) and late (^{226}Ra) peaks [ibid., v.3, s.6.4(b)].

E.52 Variant calculations were also made to examine uncertainty as to 'subsurface routeing' [ibid., v.3, s.6.4(b)], i.e. where a substantial fraction of activity goes directly to stream channels without interacting with surface soils. In the MASCOT calculations the total radionuclide flux entering the resource area from the geosphere is apportioned between the fraction translocated to surface soils (S) or dispersed in water. For resource areas under Temperate and Boreal climate states, S was taken 'conservatively' as 0.1 (but as 1.0 for Periglacial conditions) [ibid., v.3, s.5.2.5] and calculated with and without subsurface routeing. Nirex considers the subsurface routeing effect to be an important hydrological process and an S value of 0.1 to be realistic [ibid., p.5.12] but if the effect is discounted then risk would be substantially increased and could exceed the target. For example, for the Boreal terrestrial state, on a pessimistic view without subsurface routeing, the risk increases about 10-fold [ibid., fig.6.11]. Canadian research, at a location in what I take to be a Boreal environment, suggested that S is nearer 0.2 [NRX/15/4]. If that value is adopted then the peak risks for the 'better match' variant cases [COR/522, v.3, table 7.7] would exceed the target. It is evident that the variations possible in this single parameter can make large differences in the resulting dose and risk estimates. [See also D.38 above.]

E.53 A further variant case assumed 1000 years of absolute containment of all radionuclides in all vaults [ibid., fig.6.12] and found that after a few thousand years the risk increases to be practically the same as the base case with no containment. Another variant considered only six principal radionuclides out of the full inventory (^{36}Cl, ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra & ^{232}Th) and gave results within just 4% of a full probabilistic calculation, showing that this is a reasonable means of simplifying calculations.

E.54 <u>General findings</u>: Nirex drew conclusions about the relationships exposed by the MASCOT calculations, for example [ibid., v.3, s.8.2.3]:
- the scatter in the peak risk was not seen to depend strongly on any individual sampled variable;
- when source-term spreading time is long compared with that for the geosphere, parameters affecting geosphere spreading times have very little impact on risk;
- for radionuclides (such as ^{36}Cl and ^{129}I) that are not limited by their solubility, peak risk will be approximately proportional to flux through the repository and in turn to the effective permeability of the BVG host rock (about which there is much uncertainty, mostly about the properties of Type II features).

E.55 COR/522, v.3, fig.8.8 compares the source-term and geosphere contributions to the estimated peak risk resulting from ^{36}Cl, the dominant radionuclide in the period up to 1 million years. Nirex draws the important conclusions that the risk is not very sensitive to changes in geosphere spreading time provided source-term spreading time remains similar to the base case, and similarly not to a shorter source-term provided the geosphere spreading time remains constant, but if both source-term and geosphere spreading time are reduced then risks could exceed the regulatory target (as in a case where variant factors reduce travel time but the BVG has a high effective permeability).

E.56 Despite Greenpeace's disagreement, I broadly concur with Nirex that the source-term and geosphere spreading are largely independent of each other and therefore that these conclusions are reasonable. Source-term relates to local BVG groundwater flux (and heads and permeabilities) and to sorption and solubility factors that control the proportion of radionuclides dissolved in the repository porewater, whereas geosphere spreading will be dominated by travel time through the sandstones (rather than the BVG), and influenced by processes such as dispersion, sorption and rock matrix diffusion. Nevertheless it would appear that a simple change in the assumed apportionment between soil and water in the biosphere model could at a stroke significantly increase all risk values [para.E.52]. The scatter diagram [COR/522, v.3, fig.8.8] shows just a few percent of realisations above 10^{-6}, perhaps two-thirds in the range 10^{-6} to 10^{-7}, and most of the rest in the category 10^{-7} to 10^{-8}, but these would all shift if a change in the biosphere factor was found to be appropriate.

E.57 The Nirex 95 exercise did not make probabilistic realisations for the variant cases described in E.37-44 above, but it is possible to estimate the effects qualitatively. A variant that shortened the source-term period, by increasing groundwater flow through the repository for example, would transpose the swarm of realisation outcomes on Fig.8.8 horizontally to the left. Similarly a variant that shortened the period of spreading through the geosphere would transpose the swarm of points vertically down the diagram. Any model that reduced both the source-term and geosphere spreading times relative to the base case would shift the swarm diagonally downward and to the left, and would result in a materially higher distribution of risks.

<u>Agricultural Wells</u>

E.58 The greatest risk, at least from the early peak of radionuclide escape into the biosphere, comes from the pathway represented by the use of water from agricultural wells. These may intercept the plume of contaminated groundwater expected to spread from the repository. An indication of the development and degree of spread of such a plume is given for the base case and transient case in COR/522, v.3. figs. 2.11 & 2.12, the latter being the more relevant to agricultural wells. Deterministic 'preliminary scoping calculations' of risks were made using the program NAMMU (in 2-D mode) for ^{36}Cl and ^{129}I, the radionuclides judged to contribute most to risks from natural discharges at times before 10^5 years post-closure [ibid., v.3, p.1.2; p.1.6 top; & p.5.1]. It was assumed that at the relevant time there will be a local subsistence community of 300 individuals utilising a resource area of $10km^2$ (Temperate biosphere state) or $30km^2$ (Boreal), with defined agricultural productivity and consumption, mean life expectancy, etc. [ibid., s.5.2.2 & .3; & s.6.7], and within this territory wells will be sunk to a typical depth of 50m bOD, into the upper part of the regional aquifer (rather than just into the glacial drift), yielding water for domestic supply to remote houses and farms, for drinking by livestock and for crop irrigation [ibid., s.5.4 & s.6.7].

E.59 The risk against which the design process is to be judged is the risk to a representative member of the critical group [HMP/1/1, para.6.7]. This was defined by NRPB for land based disposal of radioactive waste [NRX/15/3, paras.28, 30 & Glossary] and paraphrased by Nirex as 'a relatively homogeneous group of people existing in the region of highest environmental concentrations who have habits such that their exposure is representative of the highest exposures that might reasonably be expected' [COR/522, v.3, p.1.1, last para.]. (NRPB says homogeneous with respect to age, diet and those aspects of behaviour that affect the risk [NRX/15/3, Glossary]. NRPB also defines the relevant dose as being that received by an average member of the critical group [ibid., paras.29 & 31].) The recent HMIP Draft Guidance document defines the critical group as comprising those members of the public whose exposure is reasonably homogeneous and is typical of people receiving the highest dose from the given source [HMP/1/1, Chap.2, glossary]. More explicitly it says that the composition should be representative of individuals who would actually receive a dose and whose exposure is reasonably homogeneous [ibid., s.6.12].

E.60 In this context, Nirex defines the potential critical group as users of agricultural wells and comprising infants, children and adults and the actual critical group as the age group that would receive the largest radiation dose from utilising contaminated well water [COR/522, v.3, s.6.7]. The risk to the critical group is taken as being proportional to the average concentration of a radionuclide in well water over the resource area, irrespective of the number of wells. This is obtained by averaging the concentration (of ^{129}I and ^{36}Cl) over the resource area at a depth of 50m bOD, the assumed typical depth for an agricultural well. The average concentration was obtained from a 2-D porous medium model and scaled by the ratio of the area of the model radionuclide plume to the resource area [ibid.]. (A 3-D model would probably reduce peak concentrations because of greater lateral spreading but not materially affect the overall average across the resource area.)

E.61 It would of course be for the regulators ultimately to judge whether the Nirex definition of critical group and manner of calculating the effective dose rates in relation to agricultural wells are the appropriate ones but they strike me as illogical. An agricultural well was assumed to abstract $1000m^3$/year, which is less than $3m^3$ per day, such a small figure that it would draw in water from only a small radius. Therefore a well of this capacity would either be sited over and draw water from the contamination plume or it would not. Direct drinking of the water accounts for by far the largest proportion of effective dose received by individuals of all ages from well water [ibid., table 5.9], and there could be scores of household wells of the assumed capacity in the resource area. It therefore seems to me that the relevant population is essentially that geographically associated with the contamination plume and in assessing the group exposure it might be appropriate to average the concentration across the main body of the pollution plume, but not across the whole resource area. The Nirex methodology seems to me to be at conflict with the HMIP draft guidance that the critical group should be representative of individuals who would actually receive a dose and whose exposure is reasonably homogeneous.

E.62 In relation to the NRPB recommendations, Nirex's definition of the subsistence community and its method of calculating the exposure and risk seem to me to be more akin to what NRPB has in mind for the period beyond about 10,000 years [NRX/15/3, para.39] rather than just a few thousand years hence when the risk is calculated to be at its peak. The Nirex methodology produced a Temperate state peak risk of $1.7x10^{-6}$ (mostly from ^{129}I and exceeding the regulatory design target) at about 4000 years post-closure. This is slightly earlier than the peak from natural discharge because the well(s) would intercept flow in the vicinity of the FHFZ rather than close to the offshore discharge points [COR/522, v.3, p.6.19 & fig.6.19]. Several of the variant cases are associated with shallower principal flowpaths and would have shallower pollution plumes, so the same agricultural wells would be likely to intercept somewhat higher radionuclide concentrations.

E.63 Thus the Nirex 95 modelling suggests that the greatest base-case risk is from the agricultural wells pathway. Nirex of course rightly regards the abstraction of water from wells as a possible means of human intrusion into the region of the geosphere that might contain radionuclides [NRX/15/2, s.4]. It is obviously very relevant to Sellafield where the shallower strata form an exploitable aquifer, yet there are many parts of Britain (including a proportion of territory in the preferred generic environments), where the upper tens of metres of strata would be expected to yield so little water that it is difficult to envisage even agricultural wells to support a subsistence community.

Alternative modelling

E.64 Greenpeace cites Glasgow University calculations similar to the Nirex 95 groundwater flow models [GNP/3/4]. Although there is less geological detail in the university model, it uses a similar 2-D line of section. However it appears to use a superseded Nirex interpretation of the geology which places a major fault closer to the potential repository than the FHFZ is now believed [eg COR/502, v.2, fig.25, or perhaps COR/517, v.2, fig.13, compared with COR/518, fig.010072]. This is not surprising since the Nirex interpretation of major geological features has been revised on a number of occasions and indeed has been significantly updated since Nirex 95 [as acknowledged in COR/518, Introduction, p.3, item (iv)]

E.65 When Calder Sandstone conductivity was varied whilst keeping BVG conductivity constant, flow rates in the sandstone showed a direct relationship to its conductivity but flow through the repository remained constant, indicating that the Calder Sandstone and BVG aquifers are de-coupled. Similarly when BVG conductivity was varied whilst keeping that for the Calder Sandstone constant, flow through the repository was found to vary directly with BVG conductivity. Importantly, the pattern of flow was found to remain similar in all cases, with upward flow at the 650-1000 m bOD depth, westwards horizontal flow beneath 1500 m, and westwards downwards flow in the BVG beneath the present coastline. Varying fault conductivities in both the BVG and sediments produced insignificant change in flow through the repository.

E.66 Greenpeace considers that the most realistic models are those that assumed a regional BVG conductivity of 1.2m/year (i.e. about $4x10^{-8}$m/second) and a Calder Sandstone figure of about 3m/y. This produces the flow pattern on GNP/3/4, fig.3(a) and particle tracks from a repository at 650m depth as shown on fig.6(a). With these conductivity values, the calculated pattern of freshwater heads [GNP/3/6, fig.18(b)] is a fair match with those observed, and there is a good match between calculated and observed heads with depth at Borehole 2, at least down to 800m bOD [ibid., fig.19]. However the BVG figure ($4x10^{-8}$m/s) is at the top end of observed values and significantly higher than $1x10^{-9}$m/s which Nirex thinks is appropriate, and the sandstone figure is lower than Nirex considers likely. Despite the apparent goodness of fit I am inclined to agree that these particular input parameters are unrealistic, but this is an example of the difficulty experienced by Nirex and other researchers of making any model replicate the observed borehole heads and salinities.

E.67 The Glasgow University modelling also considered a repository at 1000m depth [GNP/3/4, fig.7(a)]. By contrast, Nirex has not presented variant cases that explore the effects of locating the repository either deeper or further west.

Nirex 95 findings

E.68 The Nirex 95 results to which Nirex attaches most importance are that for a base case consisting of best-estimate central parameters, the calculated risks for terrestrial discharge in the Boreal biosphere are $1.1x10^{-7}$ at 20,000 years and $3.3x10^{-7}$ at 4 million years, which are numerically below the 10^{-6} design target. However for the agricultural well scenario, a peak annual risk of $1.7x10^{-6}$ was estimated, outside the target and only 4000 years after repository closure. At this stage no values should be taken too literally, but the figures do indicate that peaks in foreseeable mean risks are well within an order of magnitude of the 10^{-6} target, and simple scenarios can be envisaged under which the target could be well exceeded, in contrast with the MADA scenarios for pure BUSC sites which Cumbria advocates.

E.69 Nirex believes that ongoing research may prove that the Nirex 95 results reflect unduly conservative assumptions, in particular:
(a) the assumed immediate access of groundwater to all wastes in the base case [COR/522, v.3, s.3.3.l(a), p.3.7], which would immediately dissolve all ^{36}Cl and ^{129}I, ignores the retarding effects of the packaging;
(b) the assumed predominant escape of radionuclides through Type II features [ibid., s.3.2.4, p.3.5] ignores the possibility of designing the repository layout to avoid them, or of sealing such features;
(c) no allowance has been made for mineralisation processes in the cementitious vault backfill nor in the geosphere as a mechanism for reducing the solubility and release of long-lived radionuclides, notably the ^{238}U chain;
(d) the sorptive properties of the NRVB were assumed to be lower than experimental values because of uncertainty as to whether pores may become blocked or crack surfaces less reactive in the long-term; and
(e) agricultural wells are not likely to be as deep as assumed and ignore dilution with shallower recent meteoric water and sandstone aquifer water (v3, p.6.19).
Furthermore Nirex now says that more recent site data suggests that hydraulic connections within the BVG, and to the overlying sandstones above the North Head Member of the St Bees Sandstone, may have been overestimated.

E.70 Some or all of these 'conservatisms' may well be so, but by the same token, continued research may show areas where the assumptions have been non-conservative or that other mechanisms should also be allowed for, as for example the influence of subsurface routeing in the biosphere [E.52 above], or accelerated transport with escaping gas [C.108], or possible colloidal transport of plutonium [HMIP study FOE/8/32, p.26 2nd para.].

Realism of a 100 million year timescale and utility of Nirex's subdivisions

E.71 The assessment of post-closure repository safety concerns protection of the general public against the escape of radionuclides into the environment in concentrations that could be harmful, and the likelihood of disturbance of the repository. Factors relevant to the assessment timescale include the half lives of radionuclides in the wastes, some of which are very long; rates of nuclide release from containment; rates of transport through the geosphere, particularly in groundwater; long-term climatic and geological processes; and the evolution of humankind. The principal Nirex 95 [COR/522] transport models and risk calculations were projected from repository closure to a time horizon of 100 million (10^8) years, and debate during the inquiry revolved around this period, but the presentation of results beyond 10^6 years was justified as providing a basis for understanding the factors controlling risk and a demonstration that there is no sudden increase in risk after 10^6 years [ibid., v.3, s.6.4]. Comparable but more preliminary calculations in Nirex Report 560, 1994 [FOE/5/19] were similarly presented to 10^8 years, though figs.3.2-3.6 make clear that the period beyond 1 million (10^6) years was considered to be beyond the period of detailed assessment. The PERA report of 1989 presented very preliminary biosphere dose and risk estimates, but also up to 10^8 years [COR/501, figs.5.1 & 5.2].

E.72 Nirex has applied different timescales for different purposes. For example, PERA [ibid., para.5.6.18(c) & Table 5.2] included estimates of post-closure collective dose over time frames of 0-10,000 years and 10,000-10 million years for various generic geological settings. Comparable figures for the same two time frames were used in the 1988 MADA exercise for specific sites under the 'post closure safety to society' criteria, Attributes 19 & 20. I have already commented that the latter covers such a long and distant period that it is questionable whether realistic calculations can be made for such extreme future times [para.B.62 above].

E.73 For the purpose of describing near-field evolution, which is especially concerned with the containment or release of radionuclides after closure, Nirex has used the classification:
(a) Short term processes - hundreds of years (eg re-saturation of the repository and development of maximum vault temperatures);
(b) Medium term processes - thousands of years (eg maintenance of pH and Eh);
(c) Long term processes - up to and beyond a million years (with changes in pH and Eh, decline of most radionuclides to insignificant levels etc) [COR/528, s.3.1.1-.3], but considers that detailed numerical performance assessments of the repository and its environment are not meaningful beyond a million years. [ibid., 3.1.3 penult.para].

E.74 International guidelines speak only in general terms regarding timescales relevant to the hydrogeological regime [para.A.15 above] and geodynamic stability [A.24] except EC Euradwaste 6 which is rather specific in suggesting a 10,000 year period for demonstration of tectonic stability [A.26(a)]. As for UK bodies, the advice of NRPB and RWMAC/ACSNI on long-term radiological requirements is discussed below and at para.A.52 above. The HMIP draft guidelines prescribe no definite cut-off time for the period over which post-closure risk should be assessed [HMP/1/1, para.6.13] but assessments should cover the timescale over which the models and data by which they are generated can be considered to have some validity [ibid., para.8.23]. Within this natural limit to the timescale over which it is sensible to attempt to make detailed calculations, HMIP does not propose any particular subdivisions or degrees of detail, saying that this is a matter for the developer to justify [ibid.].

E.75 It appears to me that for overall risk assessment Nirex have been following quite closely the methodology recommended by NRPB in 1992 [NRX/15/3 (2nd doc. - Recommendations for the practical application of the Board's Statement on Radiological Protection Objectives)]. This proceeds on the basis that it is not appropriate to have a specific regulatory 'cutoff' time for risk assessment because the time for first activity to reach the biosphere may be significantly greater than 10,000 years [ibid., para.23, & endorsed in GOV/208, para.81] but that the principle of protecting future generations does not imply that modelling of risks to individuals must maintain a constant level of detail for all times in the future [ibid., para.22]. By reference to a table of historical and geological events which is included 'for perspective' (also reproduced by Nirex in its Biosphere report COR/526, p.4), NRPB is firm that 'assessments that extend into the very far future (beyond times of, say, 1,000,000 years) can have little scientific credibility, and even those with timescales of 10,000 or 100,000 years will be subject to considerable uncertainty'.

E.76 NRPB recommends, for the purposes of carrying out and presenting risk calculations, that the future should be divided into a series of time frames, and suggests intervals based on orders of magnitude [NRX/15/3, 2nd doc., para.25]:
(a) facility closure to 100 years: assumed continued institutional control [ibid., para.26];
(b) 100 to 10,000 years: biosphere conditions may remain broadly comparable to the present although human behaviour is likely to change greatly [ibid., para.27]; site-specific risk calculations should be performed for hypothetical critical groups;

(c) 10,000 to 1 million years: geosphere calculations should continue to be 'predictive', but for the biosphere and human activity need to be simplified because of increasing uncertainties [ibid., para.38];
(d) After 1 million years: beyond the expectation of stable geological formations, so qualitative, not quantitative, arguments should be used [ibid., paras.41 & 93].

E.77 The above time frames are closely similar to those recommended by a RWMAC subgroup in 1990 [quoted in GOV/409, para.3.30] and for similar reasons [ibid., paras.3.42 & 3.43]. RWMAC suggested that institutional control may last 300 years, that conditions up to 10,000 years are within the human experience, that up to 1 million years they are predictable from the past, but beyond 1 million years conditions should be regarded as unknown. (HMIP similarly thinks of control for at most a few hundred years [HMP/1/1, para.6.4] although I note that in relation to the risk of intrusion, RWMAC now suggests an institutional memory of no more than 100 years [GOV/409, para.7.4(vi)].)

E.78 10,000 years post-closure appears to be regarded as a threshold. NRPB consider that site-specific calculations relating to the biosphere and human behaviour should not continue beyond about 10,000 years, and for times greater than this, simple reference models of the biosphere and the behaviour of human reference communities should be adopted, though site-specific calculations of the behaviour of radionuclides in the geosphere may be made up to, at most, a few million years, beyond which safety cases should be primarily qualitative [NRX/15/3, paras.81 & 82]. The 1995 recommendations of the RWMAC/ACSNI group [GOV/409] were that the risk criteria for the selected DWR(s) must be demonstrably satisfied over a period of 10,000 years and beyond this arguments must be presented to demonstrate that safety will not be reduced [Summary, item 4 & paras.3.42/43]. It notes that a number of other countries (USA, Canada, France, Germany) require or recommend a similar 10,000 year demonstration period [ibid., table 1]. The EC Euradwaste 6 document [NRX/14/2, s.III.1] requires an expectation of no significant tectonic movement or effects within say 10,000 years, and at the inquiry Greenpeace argued that a repository site should be considered unsafe if the host rock permeability allowed a return of water from the repository to the surface within 10,000 years.

E.79 The IAEA 1989 Safety principles document [GOV/503, s.6.1], describing 'long time-scale aspects' considers that human environmental conditions become more and more speculative when the periods considered are 'tens of thousands of years' from now; that dose and risk assessments, in the absolute sense, may not be meaningful for periods longer than 'a few thousand years' and that other independent means may be needed to reinforce the conclusions of the dose and risk assessments 'for such long time periods'. This appears to be implying that periods of tens of thousands of years are quite long in the context of risk assessments.

E.80 Various objectors demand demonstrable safety for all future generations. I agree with NRPB [NRX/15/3, 2nd doc., para.22], RWMAC [GOV/409, para.3.30], and HMIP [HMP/1/1, paras.8.23 & 9.5] who all express the need to keep a sense of perspective about future timescales relevant to risk assessment. The future physical world, the surface environment and the performance of a repository can only be predicted with some confidence over relatively short periods and beyond that become progressively more speculative and uncertain. In making forward projections, initial inaccuracies and uncertainties become multiplied with increasing timescales. This is unavoidable. Hence an understanding of the geological past and studies of natural analogues become of great importance, to identify trends and possibilities and so far as possible to place realistic constraints on future outcomes.

E.81 I consider that quantitative expressions of risks at timescales over 10^6 years are meaningless. Over such a period there is a certainty of profound change and at timescales approaching 10^8 years continental drift, for example, will carry Britain towards new latitudes even if it escapes being affected by mountain building or subsiding into a sedimentary basin. Also by analogy with the fossil record of the last 100 million years and its history of evolution and extinction of species I believe I can say with certainty that mankind as we recognise it will not exist. I agree with RWMAC that beyond 1 million years conditions should be regarded as unknown [para.E.77 above] and with NRPB that assessments beyond 1 million years can have little scientific credibility [E.76 above].

E.82 On the other hand it is necessary to look well beyond say 10,000 years. In the case of the repository itself and its ability to contain radioactivity, 10,000 years is very short relative to the half lives of some of the radioelements and the extent to which they will decay in the near-field, even though very substantial decay of the inventory as a whole should occur within the first, say, 1000 years [see para.E.5 above].

E.83 The guidelines reasonably draw a distinction between the rates of change and predictability of processes in the geosphere compared with those in the biosphere. All but the shallowest bedrock geology and geosphere processes are likely to change relatively slowly (leaving aside cataclysmic events) but the biosphere is in a state of constant change, including the climate, geomorphology, and the characteristics of all living populations from microbes to Man. The rate of change of driving hydrogeological mechanisms is less certain. It will be related to climate, the hydraulic properties of the rocks and superficial deposits, and landform, and could be affected by such factors as ice loading and changes in tectonic stress patterns.

E.84 In this and many other matters, the geological past and close study of recent trends can be used as a guide to the future. In the case of future climate conditions, an Intergovernmental Panel has felt able to make predictions for a period of 125,000 years [COR/527, p21]. The Royal Society study group [COR/605, s.6.2] rightly observed that the development of time dependent groundwater models that seek to predict changes over periods of the order of 10^4-10^6 years requires knowledge of groundwater states over similar periods in the past and, ideally, the ability to simulate those past changes.

E.85 Although RWMAC suggested that conditions up to 1 million years are predictable from the past, I agree with NRPB that assessments with timescales of even 10,000 or 100,000 years will be subject to considerable uncertainty, especially the range of possible biosphere conditions and human behaviour [paras.E.76 & 77 above]. I regard a post-closure period of the order of 100,000 years as being the maximum for which it is reasonable to give some credence to quantitative biosphere dose and risk values. Nevertheless it is informative for numerical models such as MASCOT to be run to extreme timescales such as 10^8 years, not for reliance on the quantitative values but for the useful general indication they give of the potential persistence of radionuclides, and the period(s) over which significant fluxes and doses might develop and reach a peak.

Priorities for improving quality of safety assessment

E.86 I consider that the Nirex 95 groundwater pathway study has been a good effort at setting out the methodology, assumptions and data, and presenting the broad findings as they were at the time. It is still only a preliminary study but has highlighted many of the issues and factors that will be important in making a detailed safety case. Although it has made use of numerical models and expressed results in quantitative terms, the projections into the future are not to be taken literally, but are useful in beginning to demonstrate orders of magnitude, the general gradualness of most biosphere effects and lack of 'cliffedge' effects.

E.87 I believe Nirex have appropriately been following a methodology similar to that recommended by NRPB [see E.20 above] and that this approach, in more detail and with better data, and with any adjustments required by the emerging guidance from the regulators, should be continued, that is to say: the testing of conceptual and modelling uncertainties by scoping studies, comparison of alternative models etc; devising ranges of scenarios and time variant models to address uncertainties as to long term biosphere and geological changes; by making 'Central value' deterministic calculations and testing the significance of individual parameters with sensitivity analyses; and by addressing parameter uncertainty with probabilistic calculations. In the probabilistic assessments it seems to me that a more detailed explanation than hitherto is required of the combinations of factors that may produce the more extreme dose and risk values.

E.88 Nirex 95 addresses only the groundwater pathway for radionuclide transport to the biosphere. Future work will need to address other pathways - gas, human intrusion etc - and also other processes that could influence calculated risk, such as mobilisation of radionuclides by colloids or transient effects due to climate change.

E.89 Nirex recognises [COR/507, p.16] that the most important development required in its safety assessment modelling is to be able to model time-variant effects and that to model climate change in particular will require a greatly expanded definition of the system and a very complex interface with MASCOT. Such a challenge though would appear to be common to any repository site.

E.90 For the Sellafield District and the groundwater pathway, a revised conceptual model is needed that will closely reproduce pressure and salinity distributions across that area, in particular that will generate the requisite high heads at depth by proper physical features and processes rather than having them imposed. More accurate descriptions of processes may narrow uncertainties and reduce the need for conservative assumptions, but the new model may increase the risk estimates compared with the present base-case.

E.91 All modelling needs to take account of the latest geological and hydrogeological data, though difficult to achieve when so much information continues to be acquired. The Nirex 95 study did not incorporate all the then available borehole data and is now out of date in that there are much more borehole monitoring data, hydraulic testing and pumping data, better geological mapping aided by seismic work, and so on, especially in and around the PRZ. Future work must improve the modelling of faults, as there is obvious uncertainty that faults are adequately and realistically represented.

E.92 A major limitation of Nirex 95 is that it is essentially a 2-D representation and does not cover the Site. The work has not, for example, explored the sensitivity of parallel cross sections, or of altering the repository location. Nirex itself is unsure whether it has yet optimised the repository location, and I am of the view that future risk calculations need a lot more exploration of the effect of varying the repository location and geometry within the 3-D space of the PRZ and perhaps beyond, eg a shift westward as envisaged by the Royal Society study group. This cannot easily be done within the constraints of the current, essentially 2-D, approach.

E.93 Nirex 95 does not include any engineering structures other than a 2-D representation of the repository vaults, i.e. not the repository drift(s), nor RCF galleries or shafts. Although the preliminary indications are that, if well constructed, such features may not be detrimental to the overall repository performance, future assessments will need to explore their influence and it is probable that they will need to be explicitly represented in three-dimensional models. It is also notable that variable permeabilities in the BVG, and thermal and geothermal effects have been omitted from modelling to date.

E.94 Nirex continues to gain considerable amounts of field and laboratory data and to refine and develop its models. With additional regional boreholes and continued geophysical investigations it would gain a greater understanding of the regional geology and hydrogeology and could develop better 3-D models, even without the information and experience that would be gained from the RCF. The rate of change and refinement of data and submodels is likely to be at least as rapid as in the period between Nirex Report 560 and Nirex 95, and the company has indicated that it is working on a substantial revision of its models in any event by late 1996. These will seek to achieve a closer match with observational data by incorporating features and processes that perhaps more realistically represent the natural conditions, including coupled thermo-hydromechanical effects. If the RCF is to play its intended role in the validation of models then there is a need to make detailed hydrogeological predictions as to the likely drawdown effects. However in view of the fact that current central case repository performance models give results well within an order of magnitude of the design target, I consider that it would be appropriate to make a further preliminary post-closure performance and safety assessment of the whole system even before a start is made on RCF construction, to see whether the results from these new models appear to be moving in a more or less favourable direction relative to the risk target. I am aware that this would be a large task but now that the methodology is becoming established the task should become rather easier the next time.

F FURTHER WORK PROGRAMME & ROLE OF THE RCF

Further Work Requirements

F.1 The Nirex DWR project now focused on Sellafield is a major scientific, technical and engineering undertaking involving a complex and coordinated programme of academic and practical research, laboratory work and site investigations, numerical modelling and risk assessment, and many related aspects beside. The volume and pace of research and investigation need to continue at a similar level if the many gaps in knowledge and understanding are to be resolved. Within these technical areas there are two broad aspects of the work required, firstly that concerned with the practicalities of constructing a deep repository, of placing and enclosing the wastes, and of sealing the repository when full; and secondly that of assessing the suitability of the site and the long term performance and safety of the completed repository.

F.2 Modelling: Dealing with the latter aspect first, the demonstration of the suitability or otherwise of the Sellafield site for a DWR will depend on risk assessments relying principally on numerical models and other representations of the whole repository, geosphere and biosphere system and its components over an extended time-frame. The Nirex 95 work is acknowledged to be preliminary and to address only the groundwater pathway. Model development needs to continue, as discussed in Chapter 6E above, and will need to address other pathways such as gas migration and human intrusion.

F.3 Among the factors that I have identified is the need for:
(a) more detailed 3-D modelling of the geology and hydrogeology of the District [D.54], but that 2-D modelling will continue to be important, for example to investigate both divergent flow away from the PRZ across the Seascale FZ and the influence of the Carboniferous Limestone to the north [D.53];
(b) consideration as to whether probabilistic 1-D radionuclide transport modelling can adequately represent and quantify uncertainties in patterns and rates [D.37];
(c) a better generic understanding of fluid flow through fractured rocks [D.11 & D.55], which may help overcome the difficulties in applying porous medium modelling to faulted, fractured and jointed rocks like the BVG and of defining average properties at appropriately large scale [D.13 & 14];
(d) coupled thermo-hydromechanical (THM) models to reflect the link between heat, rock stress and water flow [D.19];
(e) a better generic as well as site-specific understanding of the effects of excavation disturbance and changes in rock stress patterns on groundwater flow [D.21];
(f) more generic and site specific understanding of gas flow through the geosphere [D.22];
(g) improved modelling of faults - Nirex accepts that the major faults may be sufficiently variable for each to require a different modelling approach (in which case it would appear appropriate for each to be individually investigated) [D.24 & 38];
(h) the representation of time-variant and transient changes over the timescales under consideration by the definition of scenarios to reflect major changes in climate and geography, and in conditions and processes in the system from repository to biosphere [D.26, 27 & 56];
(i) the definition of assumed scenarios about human actions and contact with contaminated materials to assess the likelihood and risks of human intrusion events [D.30];
(j) modelling in more detail the effects of the construction and operational phases of the proposed RCF on groundwater conditions and how the RCF might affect the post-closure

performance and risk of an adjacent repository, i.e. an up-to-date equivalent of Nirex Report 560 [D.57];
(k) recognition that conditions and processes going on at depths well below the proposed repository could have an influence on groundwater flow and geochemical conditions and need to be incorporated in the models [D.58].

F.4 To overcome some of these matters, Nirex indicates that it is working on a major revision of its overall conceptual hydrogeological model by late 1996. This is appropriate because the overall model needs to closely reproduce pressure and salinity distributions across the District, especially the high heads at depth, by proper physical features and processes. To do so will require more detail, the incorporation of more processes, and further calibration [E.52 & 90]. However I have already expressed the view that as the current central case repository risk assessments give results well within an order of magnitude of the design target, and as significant revisions to the models are imminent, it would be appropriate to make a further preliminary post-closure performance and safety assessment of the whole system even before a start is made on RCF construction [E.94].

F.5 <u>Data Acquisition Requirements</u>: Modelling requires data, and the validation of models requires fresh, independent data [D.47 & 59]. It seems to me that new data are required in almost all areas of work pursued to date. Some would appropriately come from continuing laboratory work and theoretical modelling, particularly in connection with the chemistry of the repository near-field and leachate/rock interactions in the geosphere, and there should be continued generic research and analogue studies on long term processes. Above all there is a need for much more site data, and at a wider range of scales to assist with upscaling [D.59]. The results of site work can also be applied to repository design and engineering.

F.6 The basic geology and hydrogeology of the Sellafield region is a primary consideration. Significant revisions in the interpreted geological structure and stratigraphy of the PRZ and Site were made even in the months before the inquiry and the process is likely to be repeated as more data are acquired. There is a need for better mapping and model representation of the geology in three dimensions, to below the depth at which it may be influencing, or may in the future influence, the regional groundwater flow - across the whole District in fair detail, in better detail across the Site, and in close detail in the volume of the PRZ and perhaps somewhat to the west also [E.92]. If an adequate comparative assessment of the BVG basement rocks within the volume of the PRZ is to be made, I consider a detailed understanding of the geological structure and stratigraphy is required in the PRZ to the maximum envisaged repository depth because at least general associations can now be demonstrated between physical and hydraulic properties and particular stratigraphic and structural divisions [C.80 & 134]. The RCF could assist but in only a limited proportion of the 3-D PRZ space; continued geophysical surveys will be important [see G.30-32 below].

F.7 There is a need for more information on the location and characteristics of the faults, and whether particular faults or portions of them act as significant barriers to flow or conductors, as there is obvious uncertainty that they are adequately and realistically represented in flow models [E.91]. More data to assist in dating faults and fracture infill materials are needed in the context of demonstrating tectonic stability and the persistence of groundwater flow networks. The RCF would give good opportunities to sample from fractures but would be of only limited usefulness in respect of faults [C.126 & C.141].

F.8 In the area of basic hydrogeology, there is a requirement for better understanding and representation of recharge conditions and flows on a District-wide scale, and in lesser detail on a regional scale [C.37 & 38]; a better knowledge of just where groundwater discharges occur [C.46]; a better definition of the 3-D salinity distribution and the STZ, even at the Site scale [C.53]; and high quality, detailed determinations of groundwater chemistry even at locations well distant from the PRZ [C.58]. I also believe insufficient is known about head, density or water chemistry differences across any of the faults. All these factors highlight a need for more, and better distributed, data points, principally more deep boreholes.

F.9 Crucial to the safety case calculations are effective large scale hydraulic properties for the major hydrogeological units incorporated in the hydrogeological conceptual model (currently 14 but continued investigations may show that more or a different definition of units may be appropriate), and values for dispersion and rock-matrix diffusion, but these input data are subject to considerable uncertainty and have included reliance on inference, elicitation and upscaling from small scale sampling and measurement [E.25], so there is a need for much more direct site data and at the largest practicable scales of observation. The major uncertainty is the nature of the fracture systems, fracture flow and connectivity [E.30].

F.10 Work is needed to see whether any closer associations, beyond the numerous apparent partial correlations thus far demonstrated, can be found between flow zones and particular geological characteristics, but there appears to be an association between BVG flow zones and faults that would justify considerably more attention to the latter [C.88 & 89]. There also appear to be broad correlations between particular BVG stratigraphic units and fracture frequency and/or flow, but average properties may vary significantly even on a coarse scale because of factors such as lateral changes in lithology or the influence of cooling contraction joints [D.14 & C.79].

F.11 Influential on the outcome of flow modelling and risk assessment is the degree to which there are fairly direct hydraulic connections, local or perhaps more general, between the BVG basement and overlying sandstones. This possibility has not yet been adequately confirmed or discounted, borehole test results having been somewhat contradictory, and is best investigated by large scale artificial lowering of the groundwater [C.87] as would result from the RCF shaft sinking.

F.12 Since variant models that incorporated a distinctive deep hydrogeological unit or which imposed defined heads and salinities along the 3.5km deep bottom boundary of the model achieved a better representation of actual groundwater heads than the base case, there would appear to be a need to collect data on the processes as well as basic geology at depths well below the preferred repository range [E.30]. Logically this would require drilling, both from the surface and perhaps also from the RCF, to significantly greater depths than even the deepest preferred repository range.

F.13 In the area of basic science, there are remaining uncertainties over solubilities and thermodynamic data for individual radionuclides, especially under conditions of high alkalinity and varying salinities, and in the presence of organic degradation products [C.93, 115 & 120]. More research is also needed on sorption reactions with relevant rock types, notably those of the BVG, and particularly the effects of alkaline leachate [C.94 & 96], and on diffusion coefficients and accessible porosity of the rocks [C.97], work that to date has been mostly laboratory based. The chemical behaviour and evolution of the cementitious vault backfill is a key element in the Nirex DWR concept and is a field requiring considerable continued, predominantly laboratory based, research [C.103].

F.14 Continued general research is needed on long-term processes that require to be incorporated in transport and risk models. These include climate evolution (with associated evolution of landforms) and the transient effects of climate change [C.133]; and the influence of subsurface groundwater routeing in the biosphere [E.52 above].

F.15 Seismic monitoring and general research into the seismic vulnerability of the West Cumbria region will be useful, although the period of recorded history is short [C.129] so geological evidence of past tectonic history will be very relevant [C.141].

F.16 Practical research is needed into the physical aspects of gas migration through rocks relevant to the Sellafield site, and chemical effects and radionuclide transport consequences of gas migration [C.108 & 110]. There is need for better data on natural colloids in the Sellafield groundwater system, and for research on colloids that will be formed in the waste and cementitious backfill, and their influence on radionuclide transport and sorption [C.117 & 119].

F.17 As an aid to repository design and construction, information is needed on the geotechnical properties of rocks and superficial strata in the PRZ, and on the likely extent and behaviour of zones of excavation disturbance in both the RCF and DWR, especially consequential hydrological effects [C.111 & 143].

F.18 Practical demonstration is required of grouting techniques to control flow concentrations in the Sellafield rocks and the sealing of tunnels and shafts [C.101], and work is needed on the physical and handling characteristics of the NRVB material [C.102].

F.19 Nirex itself identifies various broad areas of major uncertainty still needing to be addressed. These include groundwater flow, radionuclide transport, natural and induced changes to the geological barrier, and repository design and construction. Nirex also specifically points to what it believes to have been unduly conservative assumptions in its Nirex 95 risk assessment [E.69]. To avoid these Nirex would need to demonstrate inter alia that: waste packaging can be assured of providing greater containment or retardation; the Type II flowing features are not as transmissive as assumed, or the repository layout can be designed to avoid them, or they can be satisfactorily sealed; mineralisation processes in the NRVB or geosphere may reduce the solubility of long-lived radionuclides; and NRVB pores will not become blocked or crack surfaces less reactive in the long-term. To do so would require a mixture of laboratory work, site observation and measurement, in situ demonstration, and model development.

F.20 <u>Nirex's programme</u>: Whilst Nirex has not spelled out all aspects of its proposed work, it is clear that it intends continuing its scientific and technical research and DWR design work along the same numerous fronts as it has to date, but with an increased emphasis on the in situ investigations represented by construction and operation of the RCF, and on detailed repository design.

F.21 An impression of the scale and balance of the proposed programme, in terms of cost and presumably also of effort, is given by NRX/12/18, table 4.2. It can be seen that, even during its 10 year construction and operational period, the RCF is by no means the largest scientific effort (in terms of cost) and that straightforward generic scientific work is still a major component.

F.22 In general it appears that the Nirex work is likely to address those areas in which I have identified present deficiencies in data, or understanding, or modelling capability [in chapters 6C and 6D above]. The difference between the Nirex programme and that which I consider appropriate is one of emphasis, most notably with respect to the proposed additional site investigations where I am in general agreement with the principal opposing parties in seeing a need for even more deep holes than planned by Nirex [C.135 & 136]. Whilst the RCF would undoubtedly make a significant contribution to characterisation of the PRZ, to in situ transport studies and to repository design, as discussed in the following sections of this chapter, there is a need for a better understanding and representation of the three-dimensional geological, hydrogeological and geochemical system over a wider area.

F.23 On that very broad scale, a significant task will be the updating of the MASCOT PSA methodology to take account of time-dependent effects of climate change and associated landform evolution [COR/507, p.16 & COR/526, fig.9]. Further research is also needed if Nirex is to meet its intention of making probabilistic, rather than single-value, calculations for key biosphere-related uncertainties such as river flow rates, radionuclide sorption values and soil-to-plant transfer factors [COR/526, pp.23 & 24].

F.24 Continued Nirex groundwater flow and radionuclide transport modelling will give more emphasis to 3-D representation and to fracture network rather than porous medium models. I note particularly that Nirex expects to develop some geosphere models in which heterogeneity within the various hydrogeological units is explicitly treated, using data principally from the RCF with an important additional contribution from the regional boreholes [COR/510, pp.19-21]. This is a recognition that large scale heterogeneity is a problem and cannot be addressed by the RCF alone.

Value of the RCF to Work Programmes

F.25 I endorse the general claims of Nirex concerning the necessity for and benefits of the RCF in addressing mechanisms of rock matrix diffusion, colloid transport, gas migration, and geosphere spreading generally; in examining the stability of the hydrogeological system over extended timescales, observing the effects of excavation and chemical disturbance, and in demonstrating the likely groundwater flux through a repository; and also in identifying geological and hydrogeological features that would enable the depth, location, layout and orientation of the DWR vaults to be refined. I endorse too the Royal Society Study Group's assessment [COR/605, s.6.6] of major problems of characterisation and validation to which the RCF will be able to contribute, notably rock fracture geometry and properties, seismic properties of the rocks (i.e. their ability to propagate shock waves rather than the likelihood of earthquakes), rock stress measurements, high quality groundwater sampling, and tracer testing.

F.26 Nirex intends that Phase 1 of the RCF Programme (described at para.F.29 and following) will provide sufficient confidence that <u>regional-scale</u> models (defined as kilometres to tens of kilometres in terms of groundwater movement) are "complete in respect of features and processes of importance to repository post-closure safety". It says this is achievable because, although a detailed understanding is required at the PRZ scale in order to evaluate the behaviour of the engineered barrier system and the source term spreading time, a less detailed understanding of groundwater flow through the rest of the regional system is acceptable for evaluating larger-scale geosphere transport. It considers the RCF programme will specifically contribute to a regional understanding by making possible the measurement of effective hydrogeological parameters for rock units and features at scales up to hundreds of metres, and detailed investigation of specific features such as fracture zones; by high quality hydrochemical sampling and long-term monitoring; and by stressing the BVG and overlying cover rocks on a large scale with the shaft drawdown tests.

F.27 However I would note that of the 14 principal hydrogeological units that feature in the current regional transport modelling [COR/522, v.2, fig.5.3] the RCF would realistically only influence or permit testing in perhaps half. Also, although Nirex says that defining how some of the model boundaries should most appropriately be treated is one of the main uncertainties in the regional context, the model boundaries are (purposely) too distant from the RCF for the latter to assist in their definition. Thus the contribution of the RCF to regional scale understanding will need to be greatly supplemented by further deep drilling, geological and geophysical mapping, and the collection of meteorological, hydrological and groundwater data.

Essential work in the RCF

F.28 Nirex proposes to manage activities in the RCF by dividing the shafts and galleries into 'sectors', each with its specific detailed programme of scientific activities, and conducted in three phases over an operational period of about 10 years. It intends that each sector and experiment in all three phases of the RCF will have forward predictions completed before the sector is excavated, or before the experiment is initiated. Nirex describes this as a process of confidence building, which I take to mean a series of validation cycles in its model development.

<u>Phase 1 science programme</u>

F.29 I would suppose the Phase 1 Science Programme of the RCF to be critical because Nirex is hopeful that about halfway through the period it will have accumulated enough data to validate and develop the relevant models sufficiently to be in a position to submit a DWR planning application, Detailed Safety Assessment, and Pre-Construction Safety Report. I comment on that timetable below [from para.F.87].

F.30 The RCF will offer opportunities not otherwise possible to directly observe and measure groundwater flow into excavations comparable with that of a repository, to directly observe and map the geology exposed in the walls of the shafts and galleries during their construction, and to sample and test at close range in boreholes drilled from the excavations.

F.31 The Shaft Drawdown Experiment is likely to be very informative and is seen by Nirex as being a major validation test. I agree with RWMAC [GOV/414, para.18] that to be useful in that regard, it is important that the modelled prediction of the groundwater response to shaft sinking is published prior to the start of shaft sinking.

F.32 Shaft sinking will induce very much greater head reductions than achievable in surface boreholes - up to 1000 metres if one or both shafts were sunk to the maximum depth range - and I agree that pressure responses and groundwater chemistry changes in the surrounding instrumented boreholes should tend to reveal any hydraulic connections between the BVG and overlying sandstones. They should provide a powerful test of whether the Basal Beep St Bees Sandstone is a barrier to flow, as assumed in current modelling but it will be more difficult to demonstrate that Type II features do not extend as preferential flow paths from repository depth to the overlying sedimentary formations.

F.33 Groundwater sampling at close quarters from well-characterised locations in the body of rocks would be an important function of the RCF. In principle I agree with Nirex that collection of inflows to the shafts and galleries as drawdown proceeds, particularly from specially designed short boreholes penetrating a few metres beyond the EDZ, should provide high-quality uncontaminated samples from general rock zones or specific features, and long-term monitoring of changes in water composition of more transmissive features or regions during sustained drawdown, should provide valuable information on flow patterns in the PRZ. Close access to BVG groundwater in the RCF would greatly improve the chances of being able to determine accurately the in situ Eh, pH and ionic composition, and also isotopes and trace gases that are possible indicators of groundwater residence times.

F.34 Information from the RCF on groundwater flow channels in the BVG is required to address uncertainties concerning spreading in the geosphere. Also required from the St. Bees Sandstone is the correlation of the observed large scale geological structures encountered in the shaft with the hydrogeological responses in monitoring boreholes in order to distinguish between alternative conceptualisations of connected fracture systems. Probe holes drilled 40m or more below the shaft ahead of construction will be hydraulically tested primarily to identify potential inrush hazards to construction but may also induce a response on the groundwater pressure monitoring system, in which case they may give information on the connectivity of fracture systems on lengthscales over many tens, or even hundreds, of metres. There would be a higher density of probe holes in the sandstones than the BVG because of their typically higher hydraulic conductivity.

F.35 During the shaft sinking it is proposed that there will be experiments with the injection of tracers from boreholes into the surrounding rocks. I believe these are likely to provide valuable data on flow and radionuclide transport, and on the effects of rock stress changes in the EDZ around the shaft, and will assist with the validation of the respective models. Also potentially very informative about the fracture systems is the proposal that dyed grout would be used when it is necessary to restrict inflows from flow zones, so that as the shaft is subsequently sunk through the grouted section, mapping of the shaft walls will reveal the fractures penetrated.

F.36 'Peripheral Drilling' of cored boreholes from the 650 metres bOD gallery is planned in the 9 month period following shaft sinking before the end of Phase 1 in order to explore and characterise hydraulic properties of networks of connected fractures in regions of the PRZ not directly penetrated by the RCF shafts. The aim is to further characterise the lengths, orientations, apertures and ways in which fractures forming flow channels in the BVG are connected, and the variability of these characteristics by hydrogeological testing, geophysical logging, the installation of water pressure monitoring instruments, and groundwater sampling.

F.37 The RCF will permit direct observations of fracture relationships and sampling of fracture infill for mineralogical analysis and radiometric age dating, concentrating on fractures that are significant for groundwater flow. I have already pointed out the potential usefulness of reliable palaeohydrogeological data in assessing whether significant changes have occurred in the past and may therefore occur in the future [C.141].

F.38 Drill-and-blast is the intended excavation method for shafts and galleries but FOE think that much less disturbance to the surrounding rock would be caused by shaft boring and the use of tunnelling machines. I consider that the choice is the conventional and natural one and that Nirex has advanced sound reasons for not wishing to pursue shaft boring or the use of road-headers or tunnelling machines for the galleries, including the need for access to the shaft walls for mapping and other scientific measurements and observations during shaft sinking, the advantage of being able to drill ahead, and for general practicality and economics. Although I consider that 'smooth' ('cautious') blasting is likely to be successful in minimising blast damage in the principal Sellafield rock types, the rock disturbed and loosened by blasting can be scaled off and thereby substantially reduce the enhanced hydraulic conductivity, an effect shown in Canadian URL trials and pointed out by FOE.

F.39 I have suggested that Nirex has an adequate understanding of the basic mechanical properties of the Sellafield rocks to make preliminary excavation designs but needs specific data from actual excavations of comparable depth and size [C.111]. Nirex plans an extensive programme of activities to monitor the disturbance caused by shaft and gallery excavation, with measurements of deformation, stress changes and acoustic emissions, using a range of well-established techniques.

F.40 An important type of testing, that could only be done from the underground facility, is measurement of the in situ development of the disturbance zone and consequent changes in mechanical behaviour and hydraulic conductivity of the rock as the shaft passes through a previously instrumented section installed from within the deeper of the two shafts. This is intended to be achieved by means of "before and after" mechanical and hydraulic testing in horizontal underground boreholes drilled towards, and around, the "target" shaft location from the deeper of the two shafts and I believe would yield meaningful results.

F.41 I note that the RCF shaft drawdown experiment is hoped by Nirex to be a major contributor to the DECOVALEX validation exercise, aimed at evaluating coupled models of rock stress and hydrogeology in fractured rocks. This work seems to me to be predominantly generic in nature.

F.42 Nirex expects its monitoring of excavation disturbance in the RCF to yield estimates of the <u>general</u> mechanical nature of the disturbance zone around the shafts and <u>general</u> indications and upper bounds of the changes in hydraulic conductivity within the disturbance zone - a recognition that the results may well prove to be irregular. A more comprehensive experiment - 'EDZ Experiment Number One' - aimed at further quantifying the hydraulic changes in a gallery excavation disturbance zone is planned to be carried out towards the end of Phase 1 (and therefore the results would not be available before Nirex's hoped-for decision point on whether to submit a repository application). Several underground boreholes would be drilled into the rock mass through which a gallery will be subsequently excavated, then instrumented and hydraulically tested to give 'before construction' baseline characteristics. Mechanical deformation of the rocks can be measured as the excavation passes by, and 'after construction' hydraulic characteristics can be measured. I anticipate that this would be a very useful experiment and one that I note is similar to that in the Äspö ZEDEX programme.

F.43 Nirex says testing will be carried out during shaft sinking and will continue to the point where the decision on repository depth, and consequently RCF gallery depth, is made. It is not intended to sink the shafts more than a few metres beyond the 650m bOD depth if the geology appears to be promising at that depth, and there is no automatic intention to sink one or both shafts to greater depths, up to say 900m bOD, to compare the geology and other physical and chemical conditions at those depths. I consider that it would be extremely difficult for Nirex to make a fully informed judgment about the most suitable repository horizon in the middle of the excavation works. The suitability of a particular depth and layout would, in my view, depend very much on modelling and performance assessment once data have been collected.

Phase 2 & Phase 3 Science Programme

F.44 The Phase 2 programme is planned to start soon after shaft sinking is completed so there would be a 9 month overlap with Phase 1 [NRX/16/10, fig.5.1]. If the Phase 2 programme is to be modified in the light of Phase 1 findings then Nirex would be well into it before all the Phase 1 results become available, and even further by the time those results might have been peer reviewed [see F.91 below].

F.45 The Site Characterisation and Demonstration (SCD) Experiment will include instrumenting and testing a set of boreholes drilled from a dedicated Phase 2 gallery to establish the geometry and hydrogeological properties of the connected fractures within an approximately 100m cubed volume of undisturbed BVG [NRX/16/10, fig.5.2]. The Ventilation Tunnel Experiment [ibid., fig.5.3] will involve construction of a 100m hermetically sealed, environmentally controlled gallery in which all water and moisture inflow will be collected. I consider these two experiments to be potentially very useful. However the SCD experiment is what I consider to be fundamental research and its declared objective, to establish hydrogeological properties of the connected fractures within the rock mass for comparison with detailed numerical models of the system, represents one further cycle of validation. The Ventilation Tunnel Experiment, whose stated objective is to obtain flow volumes from which estimates of hydraulic conductivity can be inferred, similarly appears to be basic research to provide essential modelling parameters, although it may also go toward possible final design of the repository.

F.46 Rock Matrix Diffusion experiments are planned by way of injection of tracers, sorbing and non-sorbing and of different diffusivities, through boreholes drilled from galleries into previously characterised single fractures and fracture zones and observing their arrival at sampling points elsewhere. A comparison of the breakthrough curves is expected to provide an indication of the extent to which rock matrix diffusion and sorption in fractures and the surrounding rock may be expected in the BVG. Additional information about the manner of tracer distribution and the extent of their diffusion into the rock matrix would come from excavation or core drilling into the experimental rock volume. Such experiments in the intended host rocks are important but I have commented that the timescales and extent over which they can be conducted are small in comparison with geological processes [C.97].

F.47 Experiments are also proposed to mimic the repository leachate plume by injection of highly alkaline fluids into well characterised fracture systems and observe fluid-rock chemical reactions. However it is accepted that the reactions are likely to be slow relative to the RCF timescale, and so the experiments would be designed to build confidence in trends rather than be definite as to expected changes.

F.48 The hydrochemical investigations require special drilling and sampling techniques to minimise contamination and avoid sample changes, such as loss of dissolved gases. In this respect, experience in other underground rock laboratories will be useful.

F.49 I have suggested a need for research into the presence and behaviour of colloids in the natural groundwater system and the advantage that the RCF would afford for sampling and testing at close quarters in the potential host rocks [C.119 & C.142]. Colloid transport experiments are proposed, involving the injection of a range of colloidal suspensions whose breakthrough would be compared with the non-sorbing tracer benchmark.

F.50 Studies of gas migration and two phase flow will follow experiments into groundwater flow. It is hoped to make use of the fractures previously characterised in the rock matrix diffusion experiments. Two types of experiments are considered important: measurements of gas entry pressure into fractures, and measurements of the two-phase flow characteristics of the fracture system. In my view, research on gas migration and its potential effects must be made by in situ experimentation and investigation in the intended host rocks [C.142 & D.21]. I agree with Nirex that the requisite experiments in the BVG need to be carried out in a facility like the RCF because horizontal boreholes are required to intersect identified and characterised fractures.

F.51 An important role of the RCF is to assist in the design and construction of the repository, and various aspects of construction and performance cannot easily be advanced without a facility like the RCF, including measurement of geotechnical properties of the rocks and superficial strata, excavation disturbance and consequential hydrological effects, and the effectiveness of techniques for plugging and sealing excavations and controlling groundwater inflows [C.143]. Nirex intends that the finalised location, orientation and layout of the repository vaults in the rock mass would be confirmed on the basis of underground drilling from the Phase 3 galleries, possibly along the line of the vaults.

F.52 A number of experiments are proposed during Phase 2 on sealing galleries (in orientations parallel and at right angles to the principal horizontal stress direction), shafts and boreholes [shown diagrammatically on NRX/16/10, figs.5.4-5.7], and the grouting of fracture zones, to test methods, materials, workmanship and effectiveness over the relatively short timescale of the RCF operations. The shaft and gallery experiments involve a quite complex arrangement of bulkheads and pressurised chambers and are likely to be difficult to set up. Similar experiments at Stripa and the Canadian URL have sometimes given erratic results [C.101] but I would anticipate that Nirex could improve on those procedures. Nevertheless all results are informative.

F.53 I broadly agree with Friends of the Earth when they say the special importance of high integrity engineered barriers, in consequence of uncertainties about the performance of the geological barrier, is not reflected in the RCF programme and point to the lack of detailed proposals for testing possible sealants such as bentonite or bitumen, or the use of cut-off collars. It is also a reasonable proposition that the design and construction of the engineered barriers needs to be closely integrated with the design of the repository because their performance depends on near-field interactions with the host rock, the emplaced wastes and groundwater.

F.54 FOE's general view is that testing of engineering solutions should, for the most part, be carried out at sites remote from the proposed repository in order to minimise the number of excavations in the PRZ, whilst accepting that final testing of the preferred systems should take place within a facility similar to the proposed RCF. In my view, experiments relating to short term physical (and many chemical) aspects of vault backfill need not be done in the RCF or even in real strata [C.102] (analogue studies being a more promising guide to long term behaviour), but sealing does need to be tried in the intended host rocks. For potential host rocks as variable as the BVG, there are numerous areas of testing that are most appropriately carried out at the specific repository site. This would be a less important consideration in say massive granites or thick rock salt deposits.

F.55 It is envisaged that the hydraulic characteristics of the EDZ may not have been adequately determined before the end of Phase 1, and so further work may be required to demonstrate the variation in hydraulic properties in the disturbed zone as a function of gallery orientation in relation to the maximum horizontal stress direction, and in the presence of faults or significant flowing features. The first type of additional EDZ experiment involves comparing the extent and magnitude of mechanical and hydraulic disturbance caused by a gallery excavated parallel to the direction of existing maximum natural rock stress (approximately NNW-SSE) with another at right angles to it, i.e. 'Stress-Dependent EDZ Experiments'. It is appropriate to explore whether the orientation of galleries has a significant effect on stability and flow, because there a marked difference between the maximum and minimum horizontal rock stress at RCF depths, a ratio of about 1.8 to 1 [NRX/14/13, s.A.12]. The second additional EDZ experiment, the 'Mine Through Experiment', is intended to measure the hydraulic and mechanical changes induced in a significant fault or fracture zone when mined through, again presumably by use of instrumented boreholes.

F.56 The current best estimate of the frequency of Type II flowing features in the BVG suggests that the RCF would cut through a number. Nirex says an important role of the RCF is to explore the possibility that repository vaults could avoid or minimise intersections by these features, and so reduce significantly the through-flow of groundwater. Although intersections by Type III features could also be vital to the DWR, the strategy is for the RCF layout to avoid them. Accordingly it will be necessary to explore these by core drilling and careful sampling remotely from the RCF excavations.

Baseline Conditions to be established before RCF Construction starts

F.57 Baseline conditions considered here are those relevant because of the long-term radiological risks associated with a DWR project and because of the unusually complex and sophisticated science and technology involved. It is necessary to be clear about the baseline conditions important to the safety case before the RCF starts, because there could be continuous perturbations from the start of the RCF until completion of the DWR. The regulator's views are summarised in COR/120, paras.4.16-20 & HMP/1/1, paras.7.20-24.

F.58 These baseline conditions are principally hydrogeological and geochemical, but I would include a good three-dimensional representation of the geology and definition of geotechnical parameters such as in situ stress fields and also geothermal data. As for the basic hydrogeological parameters, background data on groundwater heads, water balances (recharge, discharge, abstractions etc), hydraulic characteristics of the rocks, and flow rates and patterns are relevant and in considerably more detail than for, say, a surface landfill proposal. The geochemical factors relate to the groundwater chemistry - notably major and minor chemical species in solution and their concentrations, pH, Eh, and dissolved gases, including palaeo-indicators - and to the mineralogy of the rock matrix and the surfaces of joints or other potential flow zones. The guidance also includes background radioactivity in appropriate media, which I take to include its sources in the underground and surface water, rocks, soils and sediments.

F.59 PERA indicated that the purpose of establishing background levels and conditions is to provide a baseline for the assessment of future performance [COR/501, table 5.1, (d)]. As Greenpeace asserts, baseline conditions must exist and be demonstrated and recorded before one can perform other tests. There is a need for baseline data against which experimentation, testing and modelling can be compared and related, and specifically against which the separate and combined effects (from construction to post-closure) of the RCF and DWR can be judged.

F.60 Nirex considers that the RCF is needed as a means of acquiring data for validating long-term safety assessments but FOE assert that before work on the RCF can commence, the Nirex research programme and data set must be properly validated against existing baseline for all areas, otherwise there will be no reliable context against which to assess the proposed below-ground programme of work. Whilst that is an ideal objective, it seems to me to be unattainable in practice. I think it unlikely there would ever be the situation, when trying to characterise, prove and model a specific set of rocks at a specific locality for a one-off project of this complexity, that all models and data are validated, baseline conditions established in advance, and processes that will disrupt the hydrogeological regime through excavation are understood to a standard fit for repository post closure performance assessment in advance of any excavation. I believe there will always be some parameters that can never be satisfactorily measured, tested or modelled without having first hand experience of more-or-less the precise location at which the facility is proposed.

F.61 I do agree with FOE and Greenpeace that there can be a paradoxical situation: prior to construction of the RCF there ought to be a settled regional flow model against which the drawdown effects can be compared; that would require all boreholes whose data are used in compiling the 3-D regional model(s) to have achieved 'equilibrium' before the data can be relied on; but an objective of the RCF is to obtain hydrogeological data that can be used in upscaling to produce a better validated regional flow model.

F.62 <u>Where and when baseline needs to be established</u>: The greatest perturbations of baseline conditions will come from construction of shafts and the repository itself. There is a need to be sure of the radius of influence of the RCF, and to be able to distinguish between natural variations and induced effects, but the Nirex timetable means that there might be no period of recovery before more widespread drawdown effects from the repository itself [F.81 & 82 below].

F.63 The emphasis has been on the neighbourhood of the RCF and it is evident that baseline conditions need to be established in all boreholes in and immediately around the PRZ prior to the start of RCF shaft sinking. It is also clear that before Nirex can prepare the final safety case and commit itself to a particular DWR, all regional boreholes must have settled down so that the developer fully understands them. However I regard the regional monitoring holes, existing and still to come, as part of one system and consider there is a strong argument that baseline should be established in all of them over the wider area before a start is made on the RCF. Fundamentally this is because the RCF cannot fulfil its role of completing the regional picture if the rest of the picture is not painted in first.

F.64 I am in general agreement with Cumbria, FOE and Greenpeace who each advocate land-based and offshore boreholes additional to those proposed by Nirex. These would be needed to provide the sound understanding required by HMIP. But all or most of them would be beyond the PRZ and any direct short-term influence of the RCF. The data they would yield could not be obtained from the RCF. Simply to monitor natural conditions in these further boreholes would be of limited value in the upscaling of regional hydraulic properties of the rocks and the construction and validation of hydrogeological models, so borehole pumping tests, for example, would be useful but must be done in a controlled and measurable way [D.50]. This would require baseline conditions to be established in advance, but even if not so tested, the new holes would need time to settle down. Ideally too, holes would be sufficiently close that inter-borehole effects can be observed.

F.65 FOE define baseline conditions as being established when relatively stable or predictable environmental heads and geochemistry have been observed over a period of 4 or 5 years at all existing and proposed monitoring points, and other opponents suggest similar criteria. I agree in respect of the primary network of existing and proposed boreholes needed to fill out the 3-D picture across the District but this should not preclude the addition of secondary monitoring holes in years to come after the primary baseline conditions have been established.

F.66 Heads: I have already noted that baseline conditions are not necessarily static or constant but are likely to be responding to long term geological, geomorphological and climatic change [D.48]. For most practical purposes, including predicting the disturbance caused by the RCF itself, I consider that baseline groundwater conditions are represented by the observable average and range of measurements under natural conditions over a period of a few years [D.49].

F.67 I have also commented on the amount and period over which monitoring records are available [C.13 & C.39]. Whilst there are some long series of monitoring data these are predominantly for the sandstones and superficial deposits. There is less information on the limestones and only recent Nirex data on the BVG. The available series of local borehole monitoring data of up to 20 years gives a good indication of annual fluctuations and trends, and confidence is reinforced by a degree of correlation with monitoring records for other groundwater resource areas around the country. I consider therefore that there is a generally good understanding of the water heads at shallow depth in the boreholes over the Site area and that Nirex is close to settling baseline head data, even in the holes affected by the RCF3 pump testing, but that the monitoring period has not been long enough to show slow trends in the deep BVG [C.39 & C.138].

F.68 In the case of borehole water levels and pressures it is not necessary to know that a system has returned to complete baseline conditions following the effects of drilling, sampling and testing because the variations are often less than the limits of accuracy in the modelling [D.49]. Nirex considers that all boreholes now show constant head or systematic seasonal variations [NRX/14/13, section B.2] and that this evidence of baseline conditions has been confirmed by independent review [NRX/14/3], but in my view this was premature [C.39], so although monitoring would continue until the start of shaft excavation (in December 1977 on the Nirex timetable), the intervening period is not likely to be long enough for any responses in the deep BVG to annual rainfall trends to become characterisable.

F.69 Monitoring to characterise natural head fluctuations assists with interpretation of hydrogeological properties of the rocks and these fluctuations need to be allowed for in measuring artificially induced changes, such as pump testing and the drawdown caused by RCF shaft excavation. Long term fluctuations have been identified but only in records of the longest-monitored shallow Sherwood Sandstone Group boreholes [NRX/14/13, s.B.2.11].

Seasonal variations have been recognised in the sandstones but not in underlying formations except in the upper parts of the BVG in boreholes 8A/8B [ibid., s.B.2.12] in the supposed recharge area. I note that 12/13 hour (semi-diurnal) fluctuations, the same frequency as the tides, have been identified in the instrumented boreholes [ibid., s.B.2.14] but that various zones in BH 4 have semi-diurnal fluctuations that are out of phase with other test zones, one such appearing to coincide with the depth of head increase at around 800 metres bOD [ibid. s.B.2.15]. Nirex itself says the cause of these phase shifts is not yet understood but they suggest to me unidentified hydraulic connections, perhaps related to a 'Transmissive Feature at Depth' mechanism.

F.70 Hydrochemistry & Geochemistry: Precision is more important with groundwater chemistry than with, say, heads and pressures, when establishing baseline conditions because small variations in ionic concentrations, pH and Eh can significantly alter reactions, the stability of particular chemical species, and equilibria generally [D.49]. Such baseline data will assist with the development of the regional groundwater flow model and help identify the processes leading to the distribution of the main bodies of water present, and at a detailed level are required to assist in evaluating specific mechanisms and pathways. Palaeohydrogeological indicators also point to the origins and movement of the different water bodies.

F.71 Nirex considers that water chemistry data for samples taken from cores and during hydraulic testing of the deep boreholes, corrected for contamination effects of drilling fluids, have established baseline geochemical conditions of 'major variables' for the region as a whole so far as existing investigatory techniques allow [NRX/14/13, section B.3]. The data, it says, are at least 'fit for current purposes', including construction of the current regional flow model, but they do not include pH and redox, which Nirex says were always intended to be established underground in excavations of the RCF type.

F.72 I agree that the broad composition and distribution of groundwater attributable to the different regimes is now relatively well understood, but principally along a 2-D transect rather than across the whole Site and District [C.52 & 53]. There is a need for better coverage over these wider areas. Moreover, repeated sampling and testing are required to give confidence that the samples are the least contaminated that are practically obtainable. Until recently at least Nirex's contractor was unable to make a complete enough 'best estimate' for in situ groundwater composition for the purpose of modelling water/rock interactions because of uncertainties over natural temperatures, pH and Eh [CCC/4/7, 2nd page].

F.73 The RCF will afford Nirex its best opportunity to obtain uncontaminated, undisturbed samples of the groundwater, particularly from the BVG, as it drains towards the excavations, but would make no direct contribution to information on geochemistry in the more distant parts of the District relevant to the flow modelling. Nirex intends that gaps in the spatial coverage outside the PRZ be filled by drilling from the Borehole 9 site and by Boreholes 15-18 [NRX/14/13, s.B.3.6; & NRX/14/12, table 6.3(a)], the latter being specifically 'geochemical' boreholes in which collection of high quality hydrochemical data takes precedence over other measurements. [See NRX/14/7 & -8 for details of holes 15 & 16.] Cumbria, Greenpeace and others are concerned that these further boreholes planned by Nirex will not deal adequately with baseline geochemistry, and I have already expressed the view that yet more holes are needed for both physical and chemical data [C.53, .135 & .136].

Potentially deleterious impacts of the RCF

F.74 As regards the geological or hydrogeological aspects of the potential impacts of the proposed RCF, I consider these fall into two general areas: firstly those associated with the RCF alone as though it were no more than an exploratory mine or rock laboratory; and secondly its effects on, or in combination with, an adjacent radioactive waste repository.

F.75 Although a prime purpose of the RCF is to observe drawdown caused by shaft sinking as a means of validating groundwater flow models, I have already noted that Nirex did not submit to the inquiry any document that quantifies the anticipated impact of the current RCF proposals on baseline hydrogeological conditions, nor indeed on the long-term repository safety case [C.66 above]. However reference was made to the preliminary scoping study Nirex Report 560 [FOE/5/19] for a similar though rather smaller RCF [see C.68].

F.76 If the RCF is considered in isolation, simply as a mining project of limited underground extent and of just a short number of years duration, and on the basis of the out-of-date Report 560, it seems to me unlikely that the development would have a significant adverse effect on local surface or underground water. During the operational life of the mine, there would be a flow of water towards it, so the relevant factors are the effect on groundwater heads and the quantity and quality of water requiring to be pumped. After closure, and assuming the mine is sealed as proposed, then the groundwater flow pattern could be regarded as returning to something close to the original natural state (although those differences from the original state would become very significant when it comes to the underground disposal of radioactive wastes).

F.77 Report 560 considers that RCF inflows would most probably be no more than a few hundred cubic metres per day [see C.68 above]. On this basis, and even though heads in the BVG would supposedly be affected for at least 1km radius, I would expect the drawdown in the shallower sandstones to be sufficiently small and widespread as to have no material effect on surface watercourses or any shallow wells or boreholes in the district. I understand that Nirex currently has a planned pumping capacity of 650 m^3/day (7.5 litres/second) to cater for peak pumping during shaft sinking of 425 m^3/day (for one shaft), and long term average pumping (including some process water) of 185 m^3/day, which are all within the range discussed in the out-of-date report. However that document does also talk of a small probability of inflows in the thousands of cubic metres per day, and expresses the view that the RCF impacts could be considerable.

F.78 The water pumped from the RCF will be saline (except whilst shaft sinking through the main thickness of sandstones) and would be unsuitable for direct discharge to a surface watercourse, but I note the intention is to dispose of it to sea via the effluent pipeline and Calder Interceptor Sewer.

F.79 However if one then has to take into consideration the association of the RCF with a DWR and the possible radiological consequences, then much smaller and more subtle hydrogeological and geological changes become very relevant. Small changes and effects, and slow processes multiplied over long timescales, can become of crucial importance.

F.80 FOE in particular argue that the presence of the RCF shafts and galleries will introduce potentially more hydraulic conductivity and so could alter the hydrogeological regime and baseline conditions. Moreover, they say, a redundant RCF could potentially damage the repository safety case because flow through the sealed shafts and roadways could increase groundwater fluxes through the repository vaults and shorten travel times between the repository and the biosphere, and Nirex has not demonstrated its ability to seal them adequately.

F.81 I would say that the RCF as proposed by Nirex - a smaller version of a repository at a closely similar location - must alter the local hydrogeological regime and baseline conditions. The construction and maintenance of what is in effect a small mine for a period of years will inevitably alter the status quo, and if the construction of a repository were to follow closely behind, the hydrogeological conditions would not start to recover until after the closure of the repository decades later. There would be no opportunity to observe the effects of groundwater recovery and the new equilibrium if the RCF were simply abandoned and sealed following the investigations. A usual and important element of drawdown experiments is to be able to observe and analyse the recovery phase following cessation of pumping, as well as the drawdown itself, but there is no RCF recovery phase in the Nirex programme nor capacity for it in the timetable.

F.82 If a start is made on DWR construction before the RCF is abandoned and sealed, then the effects of DWR drawdown will be added to that from the RCF. The DWR will cause drawdown of its own towards the vaults and unlined sections of the access drift(s) and/or shafts. A drift or drifts from the vicinity of Sellafield Works to the PRZ [COR/206] would face significant water problems in being driven through the Triassic sandstones and would require hydrostatic lining similar to that proposed for the upper lengths of the RCF shafts. It would be expected that drawdown effects from a repository would be greater than those from the RCF because the repository vaults would be much more extensive and of greater cross sectional area than the RCF galleries, and the length of its access tunnel(s) would be some thousands of metres rather than the hundreds of metres of RCF shafts. The area of influence of drawdown from the repository is likely to be somewhat to the west of the RCF, reflecting the location of the vaults and drift(s).

F.83 In discussing Report 560 [C.48] I considered that the predicted great lowering of heads in the BVG adjacent to the shafts and some reduction over a wide radius, maintained over a period of years, would draw in groundwater from a distance and probably water of different geochemistry from that now present in the immediate locality, and on that basis would certainly alter the baseline conditions. The pumping figures now suggested by Nirex are of the same order of magnitude.

F.84 These are not, of course, arguments against the principle of the RCF, but reasons for insisting on the establishment of baseline conditions by best practicable means before the RCF is begun. One valuable role of the facility would be to demonstrate in a direct manner the effects of a small scale version of a DWR. Provided baseline conditions are as well established in advance as practicable and the perturbations from those baseline conditions are well monitored and understood, then the RCF will have performed an important function.

F.85 Turning now from the drawdown effects of the operational period to the post-closure influence of the RCF on the repository, I noted some of the findings of Nirex Report 560 concerning the indirect effects of the RCF because of its proximity or physical interconnection with the potential DWR in para.C.69 above, and concluded that the preliminary calculations in the report showed that by introducing additional hydraulic conductivity into the hydrogeological regime the RCF could indeed potentially damage the repository safety case.

F.86 The RCF shafts and repository access tunnel are not modelled in the Nirex 95 performance assessment as it was assumed that they will be adequately sealed [para.E.24 above], but Nirex Report 560 made preliminary calculations with values of permeability for the sealed shafts and drifts of 10^{-14} m^2 for a typical situation, to 10^{-12} m^2 for poor fill. (These values equate to 10^{-7} and 10^{-5} metres/second respectively.) The latter would be regarded as a very permeable fill, similar to an open-textured sand, and the former to a material that is fairly permeable in the present context. By comparison it is a typical regulatory requirement, as Cumbria has noted, that clay layers used in conventional landfill lining have a permeability better than 10^{-9} m/s. It is Nirex's case that it could easily better the values assumed in the modelling calculations. I agree: in principle it should be possible to install multiple cutoff collars and very low permeability sealing layers in a shaft or drift should that be necessary, but I also agree with FOE that Nirex should demonstrate this in detail by best practicable means before the RCF starts, to confirm that there is no significant risk. This is particularly important because it is envisaged that the RCF might be connected by excavation to the DWR. FOE's view is of course that the entire RCF should be part of the DWR.

Realism of Nirex's timetable, phasing and expectations

F.87 An RCF developed at the preferred depth of 650m bOD would involve sinking twin shafts with a combined depth of about 1500 metres, driving galleries with a combined length of between 1500 and 2000 metres, forming various insets and a short underground shaft, drilling numerous though mostly short boreholes from the shafts and excavations, and conducting a number of major experiments [NRX/16/10, figs.5.2-6.2]. Construction of the shafts and immediately adjacent galleries is expected to take approximately 3½ years, with further periods of Phase 2 and Phase 3 gallery construction activity of about 6 months and 8 months respectively [ibid., fig.5.1]. The total period of observation and testing, from the start of shaft sinking to preparing to finally seal the facility, would be almost 10 years, of which about 6 years would be a period of scientific and practical activities directly in and adjacent to the preferred repository horizon [ibid., fig.5.1]. It seems to me that the anticipated timescales of shaft sinking, gallery excavation and major experiments are realistic, and reflect the cautious rate of progress necessary if detailed observations are to be made and quality samples obtained.

F.88 Nirex considers it will gain sufficient observational data within a short period after entering the BVG about spatial variability in fracture densities and properties, that it will be possible to use refined stochastic descriptions to make and test revised predictions for the final stages of the shaft drawdown experiment during the 9-12 months between first entering the BVG and reaching the (650m bOD) shaft bottom. On this basis it hopes to be in a position by the end of Phase 1 to select the preferred, most appropriate conceptual models of flow in the BVG and each of the other formations, and an updated flow model for use in the safety assessment work. During Phase 1 of the RCF it also expects to validate the description of spatial variability in key features of the rock mass, in particular lithology, fracture type, fracture orientation, and fracture frequency and fracture mineralisation patterns; models of rock stress and stress distribution; hydrochemistry; and models of excavation damage effects.

F.89 Nirex describes some of the Phase 2 & 3 work as iterative testing, which I take to be akin to further validation cycles or refinements of models [see D.45]. However so much new and relevant experimentation and testing is proposed for Phases 2 and 3 on the topics noted in the previous paragraph that I cannot believe that any of these models are likely to be reasonably described as being validated altogether fit-for-purpose by then. There would be further fracture data from the mapping of approaching 2000 metres of galleries plus logging of drillholes, and much more cross-hole hydraulic testing in various regions of the BVG. Moreover a central aim of those later phases is said to be the testing of the ability to upscale the preferred BVG flow models. That I consider to be another, essential validation cycle.

F.90 Nirex indicates that it would start to prepare the detailed safety assessment and outline of the pre-construction safety report halfway through Phase 1 with a view to submitting them at the end of Phase 1. Just as the Nirex 95 report, published in July 1995 made use of data only up to the end of 1994, it will be necessary to define a cutoff date for the incorporation of new and revised data into any modelling and safety assessment. So in order to make submissions at the end of Phase 1, the latest data that could be incorporated would at best be some months old, i.e. Nirex would have the benefit of data from the shaft sinking period but very little from the driving of horizontal galleries into the target formation within the BVG.

F.91 Moreover I agree with Greenpeace that Nirex's timetable, which envisages applying for repository development at the end of the Phase 1 Science Programme, does not allow an adequate period for meaningful independent peer-review, and I note that RWMAC has also expressed doubts that the fully evaluated results of the RCF Phase 1 would be available by the time the Detailed Environmental and Radiological Assessment is completed for submission to the inquiry into the repository proper [GOV/414, para.34].

F.92 I consider that there is a need for a Rock Characterisation Facility as a precursor to a DWR and in the same potential body of host rocks. In a geological setting like Sellafield and with such variable host rocks as the BVG this would be essential. The RCF would provide an opportunity for the direct observation of features, the taking of high quality samples and the carrying out of delicate or complicated tests that cannot satisfactorily be done from surface boreholes. The mapping and hydraulic and tracer testing stand a good chance of defining characteristics of the fracture systems and rock mass on a lengthscale of tens or hundreds of metres, albeit that even at this scale they may not cope with large scale heterogeneities in the PRZ that may influence groundwater flow [D.36].

F.93 The RCF galleries are intended to be developed at the same level and in the same rocks as would eventually host the repository, somewhere between 650m and 900m bOD. However Nirex hopes not to have to go deeper than its preferred depth of 735 metres (650m bOD) and its timetable reflects this. RWMAC, describing essentially the same scheme as presented at the inquiry [GOV/414, p.29 fig.1], expressed the view that completion of the Phase 2 & 3 galleries and drilling recesses in the gallery walls would permit the characterisation of up to 90% of the PRZ [ibid., paras.21 & 22]. I believe this to be very misleading. It implies very extensive long range drilling fanning out from the RCF galleries into the distant 3-D space of the PRZ down to at least 900m bOD. The PRZ is practically 2km long and 1km wide and the RCF galleries are designed to be confined to the northeastern edge, so the exploration would involve inclined boreholes hundreds of metres long. It may be theoretically possible to drill to any point within 90% of the volume of the PRZ from another point somewhere along one of the RCF galleries, but that is not the same as being able to characterise that volume to any standard remotely approaching that to be achieved by the RCF excavations. There would also be the serious problem of sealing the drill holes to avoid their becoming highly conductive features. The only practicable way to characterise another volume of the PRZ would be to deepen the shafts and carefully drive exploratory galleries and short boreholes into it.

G PROMISE OF THE PRZ

Overall Geological and Hydrogeological Suitability of the PRZ

G.1 Comparison with basic site selection criteria: There is a consensus in international guidelines about the attributes which promote radionuclide containment. For host rock environments in general, it is unarguable that the ideal site would exhibit characteristics which include: very low hydraulic conductivity; substantial thickness; homogeneity and continuity; very long groundwater release times; and seismic and tectonic stability. Euradwaste Series No.1 [FOE/7/23, pp.30/31] requires among attributes that 'must be approximated in so far as is possible', that formation homogeneity and continuity should be as high as possible, with little or no fracturing and little or no facies change; Euradwaste Series No.6 [NRX/14/2, p.6] says preference should be given to formations having high homogeneity and continuity and more generally showing simple patterns; and the 1994 IAEA report on repository siting [GOV/507, paras.404/405] expresses preference for uniform rock formations in comparatively simple geological settings because they are likely to be more easily characterised and their properties more predictable, and a preference for formations with few major structural features or potential transport pathways whose impact on performance can be readily assessed. For the reasons explained in the following paragraphs, I consider that the Sellafield site does not stand up well in comparison with these international guidelines.

G.2 At the time of site selection Nirex's initial preference was for the 'hard rocks in low relief terrain', seaward-dipping sediments and 'small islands' generic environments but it then re-introduced the BUSC type [para.B.16 above]. By the time of the MADA exercise the BUSC concept had been identified as giving the best overall post-closure radiological safety for land-based repositories [B.29]. Now Nirex's preference is for Sellafield, which it describes as a BUSC variant but in my view is not stereotypically BUSC nor indeed falls clearly into any of the preferred categories [A.41-45].

G.3 Nirex's own declared central attributes were low hydraulic conductivity and low hydraulic gradient resulting in effectively static groundwater taking hundreds of thousands of years to reach watercourses [COR/203, para.3.1.4]. However Nirex now considers that favourable factors associated with the site are the low rate of groundwater flow through the BVG and the high flow towards the sea in the upper parts of the overlying sedimentary rocks, so any radionuclides dissolved in groundwater emerging from the BVG would be diluted by much higher flow of water in the overlying rocks.

G.4 Superficial geology: The Quaternary sedimentary cover of the district (predominantly glacial and glaciofluvial deposits) has a complex stratigraphy, necessarily simplified into 'domains' on COR/518, v.1, drawings 010027-29. These superficial deposits in recharge areas can have a significant effect on the proportion of precipitation able to enter the bedrock. In discharge areas they are likely to influence the pattern of subsurface flow, discharge into surface watercourses or bodies of water, and strongly influence the distribution of radionuclides in sediments and soils. Nirex recognises that its biosphere catchment models have not adequately represented this 3-D complexity to date and considers it necessary to adopt new computer models able to do so [COR/526, p.20 left]. However I would not describe the glacial geology here as particularly more varied than many other areas around the country where they have been examined in detail, although there are also many parts of the UK (including BUSC and other generically preferred territory) with little or no such cover.

G.5 The Quaternary sediments are likely to be stripped off in the next glaciations, if they have not been significantly eroded away in the meantime, so the current model will not be applicable beyond a timescale of at most a few tens of thousands of years if the climatic predictions are broadly correct. The district may or may not be re-covered by fresh glacial or glaciofluvial deposits, but they could have very different permeability characteristics. This is a possibility that could affect any part of the UK following a major glaciation.

G.6 Bedrock geology: The basic bedrock geology has been presented by Nirex as essentially a simple picture of sedimentary strata over a thick volcanic basement sequence, but the volcanics themselves overlie a thick, possibly slightly metamorphosed, sedimentary sequence of sandstones and slates or shales, largely ignored to date but whose hydraulic properties look as though they may be relevant, as suggested by variant heads-salinities and flow calculations. The possible influence of a large granite mass (a batholith) nearby, the deep seated core of the Eskdale and Ennerdale intrusions [GNP/3/14, p.421 rt & fig.8.2], has also been given little attention, but I consider that it could give rise to heat flux and other deep-seated effects.

G.7 As for the BVG basement rocks, these are a thick eruptive volcanic sequence for which there could have been no reasonable expectation of vertical and lateral consistency of lithology over any great distances, even neglecting considerations of faulting [B.33], but their depositional history in association with the development of a caldera tens of kilometres across adds further complexity of structure. They are well faulted and jointed, and may show irregular domains of cooling joint systems as well as tectonically induced joint sets. I consider that such host rocks are especially difficult to explore, map and characterise, and in such ground it will be particularly difficult to define average properties at an appropriately large scale. [D.14]

G.8 The presence nearby of the overlying Carboniferous Limestone is a constraining, negative factor [B.33]. The limestones may be karstic and exhibit enhanced permeability, but in any event are a potential mineral resource in their own right and also contain haematite ore bodies that have been extensively exploited in the past, so the risk of continued future human intrusion exists. Moreover there is significant current pumping of water from the mines which needs to be taken into account in District-wide water flow modelling [COR/517, v.3, s.4.6.2 & fig.4.11; COR/521, paras.4.4.4 & 4.4.6(c), & fig.3.8]. Future mine workings and associated water abstractions could be even closer.

G.9 The distribution of the Carboniferous Limestone is influenced by depositional history and faulted boundaries, both reflecting the location of West Cumbria at the structural junction between the Lake District massif and the Irish Sea Basin. Similarly, although the main body of the SSG has a relatively simple, homogeneous geology, the deeper Permo-Triassic formations show lateral facies changes because the depositional environment was influenced by this same structural control [C.77].

G.10 I consider that it is a distinctly adverse feature of the Sellafield site that it lies at this boundary between major geological structural provinces where a degree of structural complexity might be expected, even if not thought to be a tectonically active zone [B.33]. If tectonic movement is a possibility in the relevant timeframe then this is where it is likely to be concentrated; similarly where differential downwarp or uplift might be expected as a result of glacial ice-loading and unloading (i.e. isostatic movements).

G.11 The rocks of the district have been relatively intensively faulted, and though the stratigraphy and mineralogical evidence suggests that the most recent episode of faulting was perhaps 60 million years ago, the very presence of the faulting is one further complicating factor in the geological interpretation and the ability to model the groundwater flow and radionuclide transport. It also has a constraining effect on the space available in the PRZ for a DWR and its layout [paras.G.44 & 45 below], the more so because Nirex is reluctant to exploit the apparent hydrogeological advantages and possibly greater simplicity at depth, emphasising instead the disadvantages (of heat and pressure, and cost) of going deeper.

G.12 Past periods of fault movement will have been associated with seismicity. However, on the basis of the evidence presented, I do not rate the risk of incidence of severe earthquakes as being significant within a timescale of say 100,000 years. In any event I consider the repository design could avoid laterally persistent faults [see G.45 below] and that a filled repository is likely to be relatively resistant to ground vibration.

G.13 Hydrogeology: As for the gross hydrogeology of a potential DWR site, the attribute that is likely to contribute most to the radiological safety of a repository is that the site should be in a region of low hydraulic gradients, which is likely to be associated with an area of low topographic relief and hence to long, slow moving groundwater pathways [A.28/29]. In my view the Sellafield setting departs significantly from this ideal, with a distance from the BVG outcrops where groundwater recharge is likely to be taking place, to the sea's edge where groundwater discharge is acknowledged to be occurring, of as little as 6-7 km and a fall in elevation over 125-150 metres.

G.14 The broad hydrogeological pattern, let alone detailed variations over distances of up to a few hundred metres, is not simple, and the coastal location has added significantly to its dynamic complexity, and hence to its interpretation and modelling. There appear to be three distinct groundwater regimes with some mixing between. The site is located near the present day junction of the three, but whilst the Coastal Plain and Hills & Basement regimes have a predominantly geological control (related principally to the sedimentary cover and hard-rock basement respectively), the Irish Sea Brine mass, though it may owe its origin to the dissolution of rock salt deposits and expulsion of brines from basinal sediments, has a landward margin controlled by topography and sea levels. The Brine front would be expected to advance and retreat with changes in sea levels, but there may be a great time lag compared with the rate of climatic fluctuations. Such effects would be expected to be less likely with inland low-relief or basinal locations.

G.15 With regard to the characteristics of the identified major hydrogeological subdivisions I consider that in one significant respect these do not follow the preferred criteria: the Sherwood Sandstones are relatively uniform and have relatively high permeability. They lack the interbedded lower permeability formations that seem to have been envisaged in the sedimentary cover in the original generic BUSC and seaward-dipping sediments types.

G.16 The Sellafield DWR concept places reliance on relatively high flows through the SSG and dilution within those sandstones. Being a coastal location, the discharge of radionuclide-bearing groundwater to the sea, as would be the predominant situation at least until approaching the next glaciation, would provide enormous further dilution and would undoubtedly reduce the risks to the human population [E.11]. These appear to be positive attributes of the site although they are again not in the spirit of preferred criteria and would produce further uncertainty.

G.17 As for the BVG, and probably also the deeper basement rocks, these exhibit fracture flow, but this is to be expected of most potential hard rock DWR host environments. This is not a specifically adverse factor, nor peculiar to Sellafield.

G.18 The average permeability of the body of the BVG, i.e. the contribution made by matrix and Type I fracture flow in blocks between major (Types II & III flowing features), is looking promisingly low. However as Nirex has not yet found any particular association between groundwater flow in fractures and any single geological control such as mineralisation episode or fracture orientation [C.88], then I consider it is never likely to. Further work is likely to confirm a range of loose associations, or find none at all. If clear associations could be found, this would make prediction of future groundwater flow patterns under changed stress conditions somewhat easier and more confident. However under Nirex's present assumptions about the relative dominance of Types II & III features, the geosphere spreading time, and hence radionuclide transport, is not crucially dependent on very low BVG permeability.

G.19 Although it is evident that Nirex is having difficulty with characterising fracture flow in the BVG basement, and with determining the details of the in situ groundwater chemistry, such problems are likely to be common to all sites in deep, hard basement rocks. However I regard the uncertainty as to whether the groundwater in the BVG at the preferred repository depth is oxidising or reducing, and the location of the redox transition line, as a somewhat unusual and potentially serious complication at the depths concerned.

G.20 The variability of the Sellafield geological setting is such that I consider the RCF will at best produce data on only half the current hydrogeological units of relevance to the regional groundwater flow models. Whilst their properties might be upscaled with greater confidence than today I anticipate there will still be great uncertainty over the BVG because of its probable large scale heterogeneity. Based on the experience to date, I consider that the more the geology is looked at the less clear the picture will be.

G.21 The Sellafield site does appear to have one hydrogeological factor lending good support, namely the preliminary palaeohydrogeological data. These appear to suggest that the BVG groundwater in the vicinity of the PRZ, at least in the matrix of less well connected fractures, may have had a very long residence time. If it has been present as long as the oldest of dates, in excess of 1.3 million years, then the data would show that groundwater flow through the BVG host rocks under a wide range of climate and sea level states must be very very slow, indeed almost unbelievably so. If, however, the groundwater residence time turns out to be in the tens to hundreds of thousands of years then that would also seem to be very favourable, but it might well be indicative of recharge during a glacial period, and since the next glaciation could come within a few thousand years and is confidently predicted well within 100,000 years, then there could be pulses of groundwater exchange though the BVG host rocks within a relevant timescale.

G.22 Such groundwater ages do not appear compatible with the evidence of irregular groundwater heads and density variations at depth. Although it is true that head differences do not necessarily indicate flow, it is hard to conceive how variations of the degree measured to date (even when somewhat subdued after the boreholes have settled down) and the local density-salinity variations are compatible with over a million years, or even hundreds of thousands of years, of effectively stagnant groundwater conditions.

G.23 Implications of geological & hydrogeological suitability for overall risk assessment: On a probabilistic assessment I would not expect all, or even necessarily say 95% of all, values to fall below the 10^{-6} design target, because quite simple changes in basic modelling assumptions might significantly shift the scatter of outcomes for the many realisations [E.56 & 57 above]. However I believe that at this stage in the investigations it is reasonable to expect the site to come well within the target on a 'best estimate' central case for each of the models needed to cope with the anticipated range of climate states and geomorphology over the time-span of modelled predictions.

G.24 The Nirex 95 calculations, the best estimates so far available, gave base case results for a Boreal terrestrial biosphere (which might be considered a reasonably conservative case) within the 10^{-6} design target though by well less than an order of magnitude, i.e. $1.1x10^{-7}$ at 20,000 years and $3.3x10^{-7}$ at 4 million years. However for the agricultural well scenario, the estimated peak annual risk - $1.7x10^{-6}$ at 4000 years - exceeded the target [E.68].

G.25 It is true that some of the basic assumptions of the Nirex 95 modelling are conservative or pessimistic and there is a fair expectation that further research will show that more favourable parameters are appropriate; but there are also numerous relevant factors where further experimentation, testing and conceptual development is likely to go the other way [E.69/70]. I am inclined to agree with Cumbria that at this stage of preliminary assessment, the estimated risk under reasonably conservative assumptions should fall well within the regulatory target, though I would not go so far as to say that it should be at least an order of magnitude below. I would say that the Sellafield site, whilst it is not patently unsuitable, is a long way from being evidently promising, and certainly does not display the degree of promise, predictability and confidence in broad calculations that I would expect after 6 years of fresh intensive investigation.

G.26 Overall suitability of the PRZ: I consider, therefore, that the Longlands Farm PRZ falls well short of meeting what at one stage Nirex itself accepted as requisite generic features, notably very slow local and regional groundwater movements in an area of low regional hydraulic gradients, and predictable groundwater flow paths, preferably long and resulting in progressive mixing with older, deeper waters or leading to discharge at sea [B.31 & 32]. Moreover the geology of the Sellafield district is not what would be described as 'simple'. On the contrary, I consider it can fairly be described as 'complex'. It is true that complexity can be addressed by a statistical, stochastic approach, but complexity increases uncertainty, and increases the difficulty, required scale and expense of investigation.

G.27 Unless one regards the diluting ability of groundwater flow through the Triassic sandstone aquifer and the diluting effect of the body of the Irish Sea as positive attributes - both, it seems to me, contrary to the spirit and intention of the generic BUSC and seaward-dipping-sediments environments - all other physiographic, geological and hydrogeological factors of the Sellafield district appear generally unfavourable for the siting of a radioactive waste repository:

- the hilly topography and relatively steep head gradients of the shallow groundwater;
- the degree of faulting of the rocks, reflecting a location along the major, geologically persistent, structural boundary between the Lake District block and the Irish Sea basin;
- the choice of a thick sequence of extrusive volcanic rocks in which to construct the repository, rocks whose stratigraphy and structure are further complicated by their origin in a

caldera environment;
- the overlying 500 metres of water-bearing sandstones which are recognised as a significant aquifer and whose presence would be expected to encourage intrusion by way of water supply boreholes.

G.28 Taken overall, the site is not an obvious choice for its geological environment. It seems to me to have been selected because of its convenience - its proximity to Sellafield Works. The nuclear energy industry had been looking at the possibility of disposing of low and medium level radioactive wastes in the vicinity of UK nuclear sites since at least 1980. The study by the Institute of Geological Sciences [COR/616] of the potential of nuclear installations for DWR siting, shows that there has long been a hope that a site near a nuclear facility might prove suitable. I cannot resist the conclusion that Sellafield is not a natural choice and that its pursuit represents the triumph of hope and optimism over a truly objective exercise of identifying a small number of sites around the UK representing those in a favourable geological setting and, on a relatively simple but confident model, likely to meet regulatory design targets. Nirex started out facing many difficulties. As investigations, research and development of methods have progressed, it has opened up more and more areas of uncertainty and problems to be solved. Its task has become harder.

Prospects of significant enhancement of knowledge of the PRZ

G.29 Work under current proposals bearing on the PRZ: Nirex has focused its attention on a specific block of rock, relatively small in extent and more restricted still in depth, to be its preferred repository zone. Under its current proposals [NRX/14/12, table 6.3], the areas of investigatory work that have a direct bearing on the PRZ are the excavation and scientific programme of the RCF itself, some proposed additional surface drilling, and continued geophysical investigations.

G.30 The RCF shafts and galleries are intended to be confined to the northeastern sector of the PRZ and for preference to almost the shallowest depth within the nominal acceptable depth range. There is no doubt the RCF would lead to a major gain in direct geological, geotechnical, geochemical and hydrochemical data in the excavations and within radial distances of tens of metres up to 100 metres or so, i.e. that which is observed in the excavations and by probe drilling. I do not accept that it would be practicable to adequately characterise distant parts of the PRZ by forming long boreholes from the RCF. In my view the RCF will not, and does not purport to, characterise the host rocks and hydrogeology of the PRZ as a whole, but only in that quadrant and in the particular geological formations on which attention is focused.

G.31 As for the contribution by additional drilling, the only further surface-based boreholes planned in the PRZ are Borehole RCF4 on the centreline of the RCF North Shaft and completion of PRZ1, but these relate to the RCF proposal and a DWR in close proximity rather than to continued investigation on a uniform basis across the PRZ as a whole. Other proposed holes are well outside the PRZ - Boreholes 15-18 NW and W of the PRZ to investigate the STZ; additional holes from the BH9 site in a supposed recharge area; and additional holes, probably from the BH11 site into the Seascale FZ.

G.32 It is probable that surface based and borehole geophysical methods have a further contribution to make to knowledge of the whole PRZ, including further interpretation of raw data already gathered and possible additional surface surveys. In particular the high-resolution 3-D seismic surveying and cross-hole seismic tomography have greatly improved the mapping of geological structures and stratigraphy, but confidence relies on good borehole control. The difficulties of interpretation in the BVG even between closely spaced boreholes have already been discussed [in paras.C.75-78]. Seismic work might also contribute to general geotechnical properties of the rocks.

G.33 Other parts of the proposed work programme, notably general hydrological and meteorological monitoring, earthquake monitoring, and Quaternary deposits studies, would not, I believe, significantly enhance knowledge of the wider PRZ.

G.34 Construction of the RCF would inevitably significantly disturb the hydrogeology and hydrochemistry of the surrounding body of rock and just possibly also shallow groundwater or surface water. A primary task of the RCF science programme is to observe those effects so that they can be compared against modelled predictions. This requires that the baseline hydrological, hydrogeological and geochemical conditions affecting the site are established and understood in advance of the development; that appropriate hydrogeological and geochemical models have been devised and predictions made; and that appropriate monitoring installations and systems are in place. In addition, since the RCF excavations and their backfilling and/or sealing could compromise the suitability of the adjacent rocks and adversely affect the safety of the DWR whose location the RCF is intended to characterise, it is appropriate that a scheme for RCF backfilling and sealing is in place even before its construction is begun. Potentially prejudicial too are elements of the RCF scientific and engineering programme, such as blasting, hydraulic pressure testing, injection of tracer substances and gases, and extensive underground drilling, so it is appropriate that a scheme for the experimental work to be carried out in the RCF is also in place prior to the start of development. I consider, therefore, that planning conditions are necessary, in the event that permission is granted for the RCF development, to ensure that all of these matters are addressed satisfactorily.

G.35 There are a number of reasons why it would also be appropriate for Nirex to be required to demonstrate that its proposals for measuring and demonstrating baseline conditions and monitoring subsequent changes, for validating models and for the final closure and sealing of RCF excavations have been subjected to and endorsed by independent peer review. They are:

- the importance and novelty of the project, especially as the RCF may become an integral part of a radioactive waste repository and as Nirex hopes that DWR construction might start even before the programmed date for RCF closure;
- the disagreement between expert scientific witnesses from Nirex and the principal opposing parties as to how 'baseline' conditions should be defined and whether they have been established;
- the similar disagreement as to the degree of progress that has been made on hydrogeological and hydrochemical modelling;
- the disagreement over the required number and general locations of additional monitoring boreholes.

G.36 <u>Possibilities for varying the RCF proposals</u>: The physical design of the RCF and proposed work programme, at least until the end of Phase 1, are now quite closely defined, as described in COR/111. Options for changes in location or concept that would further increase knowledge of the PRZ have not been included in the application.

G.37 One possibility would be to ensure that at least one of the two shafts is sunk to the maximum assumed practicable DWR depth of about 1000 metres (900m bOD), plus some metres more for a sump, and experiments carried out at and from that depth, perhaps with shorter galleries at other levels. This would have the advantage of positively viewing, sampling and testing other potential host rocks and their geochemistry and hydrochemistry that, on present evidence, appear to offer hydrogeologically better conditions than the rocks at the 650m bOD level and locality. Deepening a shaft would be best done as part of the primary shaft sinking operation rather than later, after the shaft has been re-equipped for the scientific phase of work.

G.38 Another possibility would be more extensive but smaller cross-section exploratory galleries, but that would involve more intrusion, require more sealing, and would lose the advantage of replicating a scale at which disturbance effects may be similar to those of full size repository vaults. To be useful in providing data relevant to the DWR, the RCF needs to be close in location and similar in construction type and scale (in terms of diameter of shafts or cross-sectional dimensions of galleries), hence there are limits on changing the concept of the RCF, because to do so would assume a similar change in the proposed DWR.

G.39 Access could be made by drift rather than shaft, as at the Äspö Hard Rock Laboratory, and would expose greater volumes of rock, but would not appear to be feasible for an exploratory facility at Sellafield. It would be difficult and expensive to construct through the water-bearing sandstones, and would cause more complicated drawdown effects than a shaft. However in the BVG, instead of the essentially level galleries now proposed, it would be possible to drive inclined tunnels similar in scale but crossing and exploring more geological units. (This would be practicable with drill-and-blast excavation but probably not by machine mining.)

G.40 The proposal of objector Mr N Spendlove that there should be one RCF shaft instead of two, at least in the first instance, would I believe significantly reduce the scientific and technical gain compared with the Nirex Phase 1 programme. Leaving aside the arguments in favour of a second shaft with regard to safety and ventilation, I consider there would be a great advantage in having twin shafts tens of metres apart as proposed, one in advance of the other to afford the opportunity of mine-by experimentation and inter-shaft probing and testing.

G.41 The scope for altering or improving the RCF design and for altering or widening the volume of the PRZ explored are inter-related because there is a limit to the amount of physical intrusion that could be done without seriously prejudicing the integrity of the rock mass. The scale of the RCF is already quite large - over 1500m of galleries and more than 100,000 cu.m of excavation. I would not have thought that it would be appropriate to have a much greater volume and dimensions of excavation than that for URL/RCF exploratory purposes.

G.42 The final possibility for enhancing knowledge of the PRZ might be to relocate the RCF, for example to a more central location from which a greater volume of the BVG should be more readily accessible by tunnelling or probe drilling. However this would be more likely to further restrict the available territory for a DWR, unless the RCF excavations are specifically designed to be incorporated into the repository.

Suitability of location of the RCF within the PRZ

G.43 Unless it is to take on a predominantly generic rock laboratory role, the RCF must be linked locationally to the DWR. There is no point in exploring by means of full size excavations areas of the PRZ not likely to be able to accommodate a full size DWR. Nor is it enough merely to have explored a prospective DWR location by distant probing; an important part of the role of/work of the RCF is to examine the effects of full size excavations (though still somewhat smaller in cross section than repository vaults), but it would not be appropriate to drive galleries or sink shafts (from one subsurface level to another) extensively through the PRZ volume, otherwise the integrity of the potential host rocks would be seriously affected.

G.44 The boundaries of the PRZ were defined essentially on geological and hydrogeological grounds, and within that area the maximum territory available for a repository is constrained by the Fleming Hall and Seascale Fault Zones, the occurrence of Carboniferous Limestone, and reducing sedimentary cover in a northeasterly direction, a block about 2.4 by 1.5km, and between depths of about 650m bOD and 900m bOD [B.93/94]. This sounds a relatively large volume but it is preferable to avoid major faults. This is principally because of their potential association with preferential groundwater flow paths or conversely their action as a barrier to flow, so forcing groundwater upward, and because they make modelling more difficult by having markedly different geological and hydrogeological conditions on opposite sides. It would also minimise the risk of repository dislocation by tectonic movement though I consider this to be only slight anyway.

G.45 I have suggested that the DWR vaults should avoid not only Type III features (including F2) but preferably also the other larger-throw faults (such as F3, F205 and F207). However these form a complex three-dimensional pattern of intersecting and diverging, sometimes impersistent, disturbed zones so the intervening blocks of rock in the BVG are variable in width, to a maximum of less than about 650m and typically no wider than 200-500m [B.96, 97 & 99]. It would therefore be difficult to find any block of rock in the target BVG volume where 500m long parallel galleries could be driven in NE-SW directions (the preferred vault orientation for stability and hydrogeological reasons) without cutting across one or more of these faults. I believe, though, that it would be possible to find one or more sufficiently large fault-bounded blocks within the PRZ where the requisite number and volume of vaults could be accommodated by significantly changing the layout and orientation [B.100]. A possibility might be shorter galleries parallel to the NW-SE fault trend, and at several levels one above the other provided this does not mean going into various rock units with significantly different characteristics. Finding suitable locations and devising irregular layouts would not, I believe, take materially longer than currently envisaged for a regular vault layout, but irregular layouts would make modelling of groundwater flow more difficult (and make it all the more essential to have a good 3-D representation of the system).

G.46 At the time of the Nirex 95 assessment, Nirex assumed a repository location at the southern end of the PRZ near the Seascale Fault Zone. Its preferred location is now at the northeast, and the RCF is sited towards the NE corner. Nirex says that the change will give a better calculated repository performance and lower risk. This suggests that for Sellafield the safety case is sensitive to the precise location of the DWR within a limited area of PRZ [B.35 & B.101]. This seems to bear out my criticism that the site really does not come close to matching a generic model.

G.47 Nirex also says that by locating the RCF just up-dip of the preferred repository location there would be specific advantages in relation to its use by the repository - for drainage, and in connection with ventilation and emergency access [B.103]. However I consider that the layout of an essentially horizontal array of RCF and DWR tunnels and vaults could be adjusted in detail to guide drainage and air circulation in almost any direction, and whether or not the RCF is to be incorporated into the DWR complex then its precise geographical relationship to the DWR should not be crucial if, as Nirex believes, the shafts and galleries can be sealed to a high standard. On this basis I consider the Nirex arguments for siting the RCF at the northeast are not very strong. The principal advantage is that the BVG host rocks are shallowest there. In my view, and leaving aside the usual surface planning considerations, a case could be made out for constructing the RCF in other compass directions relative to the hoped for DWR location.

G.48 Provided that the design and execution of the RCF operations expressly take account of possible repository construction close by, I do not consider the RCF presents a serious constraint on the available volume in the PRZ for a repository [B.102]. However to be of value, the RCF needs to extend into and characterise the same fault-bounded block as will eventually accommodate the DWR.

G.49 The preferred Longlands Farm group of rocks are relatively extensively distributed across the east and southeast of the PRZ at 650m bOD so it ought to be possible to find enough space within which to construct both an RCF and a repository in that area and at that depth [B.103]. However this is not, on the evidence to date, as good hydrogeologically, and presumably therefore in terms of radiological safety case, as deeper formations [B.101].

G.50 Given the degree of uncertainty in this project, I would have thought the overriding objective in siting the RCF would be to have selected the radiologically optimum location, within the practical constraints of DWR cost, work safety and engineering. That suggests to me the need to explore more of the PRZ in greater detail before settling on the definitive site of the RCF.

G.51 On the other hand, it seems to me that the precise locational problems of avoiding faults and finding hydraulically acceptable stratigraphic units within the host rocks down to a scale of tens to hundreds of metres would be much less likely to arise in sites conforming more closely to one of the generic models.

Overall Conclusion

G.52 The voluminous technical evidence submitted to the inquiry within my field of interest has led me to conclude that the setting of the Sellafield site is geologically and hydrogeologically much less simple and more complex than would be expected of a choice based principally on scientific and technical grounds, and does not match any of the theoretically favoured types. It therefore suffers from the disadvantages which led to its not being generically chosen in the first place. As a consequence it and the surrounding district are proving difficult to explore and characterise. In particular the actual basement rock chosen is exceptionally difficult to characterise due to the nature of its eruptive volcanic origins. This and the frequency of significant faulting means that potential repository sites within this area will be severely constrained and may require compromise on layout and orientation. The geosphere uncertainties have increased the importance of engineered barriers so that there is high reliance on an artificial containment concept which is itself complex and untried. The preliminary safety case is certainly not a patent failure, but nor is it so clearly within targets as to command any substantial degree of confidence. Because of all the foregoing factors, the eventual achievement of a satisfactory standard of proof for this locality is especially problematic and uncertain. Nirex acknowledges there are likely to be radiologically better sites available around the UK, and in my view some probably have simpler geology and hydrogeology and therefore would be more readily investigable and characterisable.

I am, Sir, yours faithfully

Colin V Knipe