A model approach to radioactive waste disposal at Sellafield

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ABSTRACT

One of the great environmental problems of our age is the safe disposal of radioactive waste for geological time periods. Britain is currently investigating a potential site for underground burial of waste, near the Sellafield nuclear plant. Future leakage of radionuclides depends greatly on subsurface water flows; these must be understood from the past, to predict hydrogeology 10^4–10^5 years into the future. We have taken information from the present-day, published by the government company Nirex, and used a finite-element steady-state fluid flow computer code to examine water flows in the subsurface. We find that flow directions at the planned Repository are persistently upwards, and that geologically significant flow rates could occur. Flow rates are particularly sensitive to uncertainties of rock permeability (conductivity) measurements made from site investigation boreholes. The hydrogeology at this site needs longer term investigation before a confident and credible prediction can be made.

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INTRODUCTION

When choosing a suitable Repository site, the pattern and rate of underground water flow must be both predictable, and safe for geologically long times into the future. The diverse geological factors affecting such predictions, and some of their difficulties of measurement and forecasting have been reviewed by Chapman (1994). At the Sellafield site (Fig. 1), an aquifer of Calder Sandstone is at and below sea-level and unconformable onto 1000 m crystalline hills of the Borrowdale Volcanic Group (BVG). Nirex plan to site their nuclear waste Repository at 650 m below sea-level (Fig. 2) in a unit of the BVG which is unconformably overlain by sediments (Nirex, 1993b). This is a variant of a long-recognized proposal for underground disposal (Bredehoeft and Maini, 1981), which implicitly relies upon the adequate present-day description and reliable forecasting of the subsurface hydrogeological conditions. The geology and hydrogeological investigations of this Sellafield site are summarized by Nirex (1992, 1993a, 1993b), who recognized the possibility that the regional flow pathways surrounding the proposed Repository would be directed upwards (Nirex 1993b, fig. 13). Similar views have also been reached by ERM (1993), RWMAC (1994), and Royal Society (1994). However, none of these studies have published simulations to support their work, or attempted to quantify the flow rates and pathways involved. In 1992 when we commenced our own work, our intuitive expectation for subsurface water flows at this Sellafield site, was that meteoric water flow, driven by gravity, would move westwards through the proposed Repository site and possibly return upwards towards the surface. We have taken published data and used a finite-element computer code to: (i) *confirm* our expectation; (ii) obtain a *visualization* of the flow directions and patterns; (iii) obtain an indication of flow pattern *robustness*; (iv) examine the *sensitivity* of flow magnitudes to changes in conductivity. Examine the discharge *pathways* taken by water after contact with a Repository. Absolute flow magnitudes cannot be proved, verified, or validated by such single models (Konikow and Bredehoeft, 1992; Oreskes *et al.*, 1994). However, we see value in producing pictorial representations of flow directions which persist throughout the measured range of present-day permeabilities, and value in producing a numerical safety target which can be compared to field measurements.

APPROACH

At this site, there are good data on rock stratigraphy and geometry. However, there are many poorly known factors, such as hydraulic conductivity anisotropy, fault conductivity, and particularly the regional-scale conductivity of the BVG away from the boreholes. We know from borehole (B/H) data that the BVG has a fracture conductivity, some 10^2 greater than

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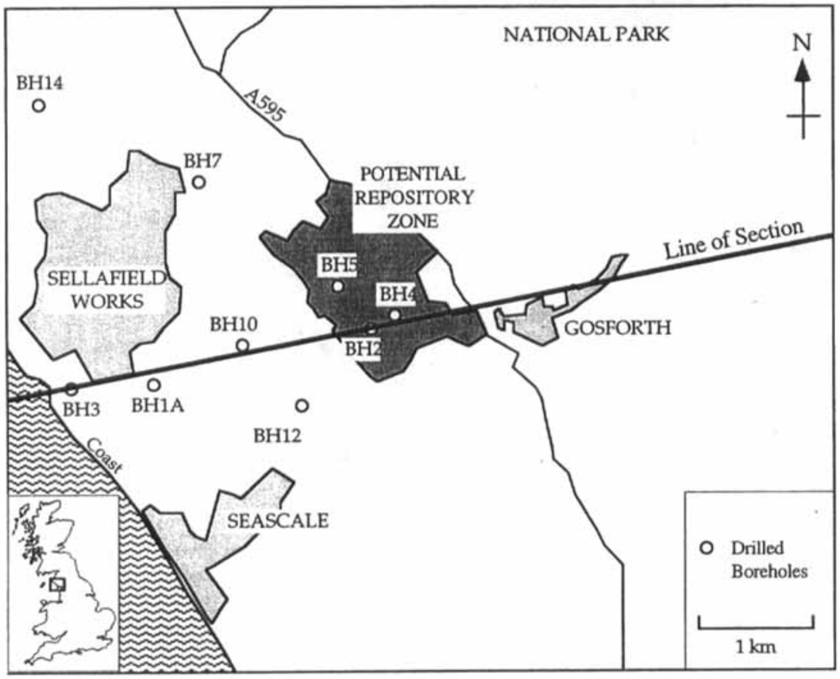


Fig. 1. *Location map of Sellafield on coastline of NW England. Locations shown for Nirex site investigation boreholes (Nirex, 1992, 1993a) Line of section in Fig. 2 starts SW of B/H 3, passes through it and B/H 2, and finishes NE on the 1000 m hills of BVG meta-volcanics.*

matrix conductivity (Nirex, 1992, 1993a,b), as do most crystalline rocks (Clauser, 1992) For the purposes of our modelling, we note from borehole measurements (Nirex, 1992, 1993a,b) that fluid flow in the BVG is controlled by fractures, which have a spacing of 50–100 m vertically. This is at least one fracture per finite element of our mesh, so that this can be treated as a matrix conductivity (Neumann, 1990).

Our approach then becomes one of testing sensitivity to different variables, by means of undertaking a series of experiments with the computer model. Before each simulation, we can vary one numerical attribute of the model. Running the model enables us to see if the result has changed from the previous experiments. If the result has not changed significantly, then that particular attribute was not important. If the result has changed, then it is important to measure that attribute as accurately as possible in the real world.

MODELLING

A geological cross-section was selected, to run SW–NE through the Repository, passing through site investigation boreholes 3 and 2, and close to B/H 1, 10, 4 (Fig. 1). This section has been extended by us both seaward and landward (Fig. 2), using public geological and topographical information Taylor *et al.* (1971). Similar sections were used by Nirex (1992, 1993a,b). The section was converted to a series of rows and columns, forming a finite element mesh of 2100 quadrilaterals (Fig. 2b), whose spatial co-ordinates were entered into a Silicon Graphics personal Iris computer workstation. The simulation code used was OILGEN, written by Grant Garven and described in detail elsewhere (Garven and Freeze, 1984; Garven, 1989). This is a generic code, formulated to study water movement in large sedimentary basins over geological time spans. The code uses a finite element mesh to iteratively solve equations of flow, based on Darcy's Law of single phase, steady-state fluid flow through a porous medium. Fluid pressure, temperature, and concentration (salinity) are coupled equations. Vector flows are calculated as average linear velocities, which are constant over individual elements, but discontinuous across element boundaries. The lower boundary of the model is impermeable to fluid flow, but allows a constant geothermal input. The upper (land) surface is the topography, so that flow can pass up or down through this. The topographically derived head of pressure is the major driving force for flow, although density induced flows are also permitted. Lithological boundaries within the mesh have no special qualities, and flow simply crosses between elements of different porosity and permeability. The lateral (vertical) boundaries to the section are impermeable to fluid flow. The code iterates until convergence of temperature change reaches less than 1 °C. Output from the code is a numerical data tabulation, which can be interrogated for each node. A graphics code displays the information visually. We have used measured data from site investigation boreholes (Table 1). Our hydraulic conductivity units are ma^{-1}, and we have simplified to ignore any variations in conductivity due to water salinity. The Repository was considered as normal BVG rock, with no additional conductivity or heat production, our assumptions will tend to reduce the circulation of water. During our modelling, the BVG conductivity range was found to be an important control of fluid flow, consequently we simulated BVG data 100 × greater and 10 × less than that actually measured, to give a wider context for interpretation. Initially, five suites of experiments were run, each time varying only one attribute of the model: salinity, fault conductivity, conductivity anisotropy of the matrix, Calder Sandstone conductivity, BVG conductivity. The last two attributes proved to be the most sensitive, so that a further 32 experiments were run to investigate their variation.

The measured salinity framework was found to be a crucial attribute. A brine 'pluton' in the lower west of the section forces westward-directed flows upwards towards the surface. The position of brine is reasonably well established from B/H data, so that all subsequent experiments were run including a brine 'pluton'. Fault conductivity was examined separately for faults cutting sediments, and for faults cutting the BVG. Changing fault conductivities for all measured values produced an insignificant change in flow through the Repository.

Subsequent models used 3.0×10^{-1} ma^{-1} for sediments, and $1.3 \times 10^{+0}$ ma^{-1} for the BVG. Anisotropy was examined by changing the BVG horizontal:vertical conductivity from 5 to 1. Surprisingly, flow through the Repository was little affected. This suggests that the direction and rate of flow in the BVG is not controlled by the shape of our finite-element cells, and that the cross-sectional area of the BVG is so large that fracture orientation may have little importance in the real world. Subsequent models used a BVG anisotropy of 5.

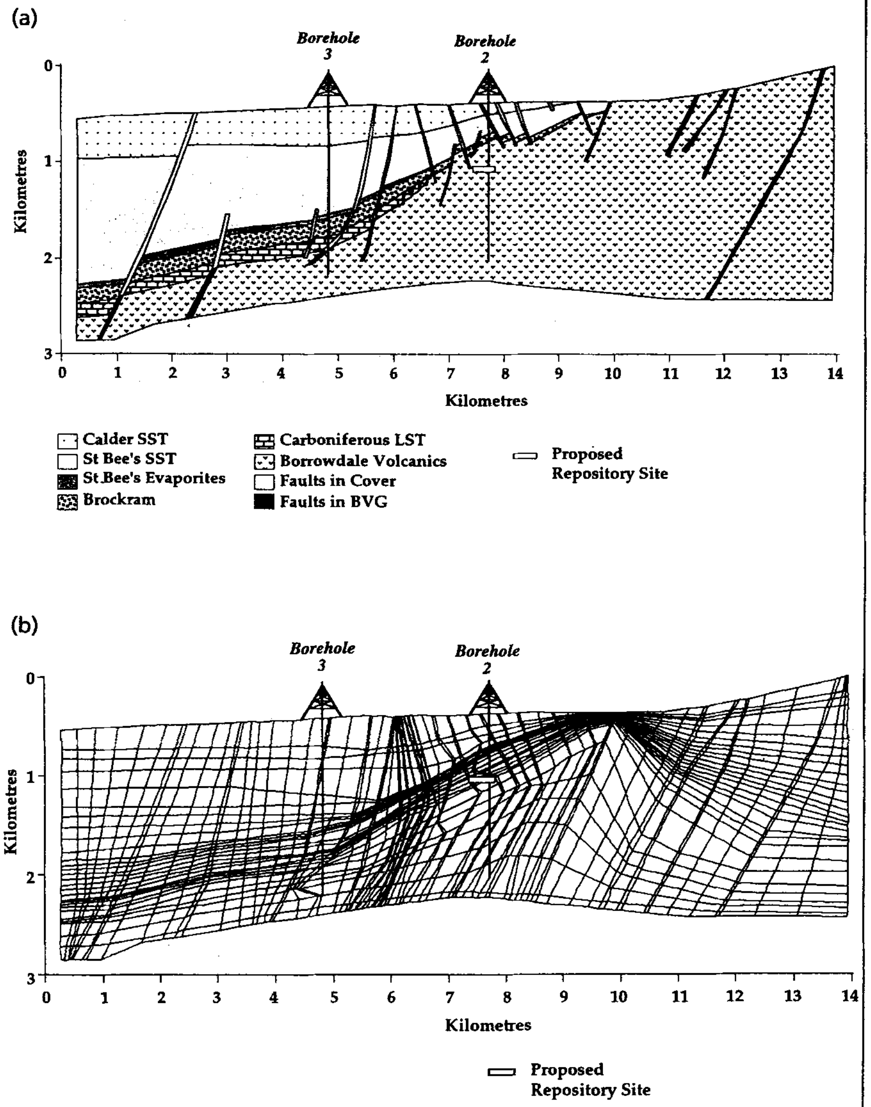


Fig. 2. *(a) Geological cross-section of the proposed Repository site at 650 m, compiled from published information by Nirex (1992, 1993a), and extended SW and NE using publically available geological information (Taylor* et al., *1971). Line of section is similar to that shown in Fig. 1. The crystalline meta-volcanics of the Borrowdale Volcanic Group rise to 1000 m elevation in the Lake District, and fall westwards to lie well below sea-level. This elevation provides a topographical drive for meteoric water flow through any fracture or matrix conductivity in the BVG. Carboniferous to Triassic sediments onlap the BVG, and provide a series of matrix and fracture permeable aquifers. (b) Finite element mesh derived from Fig. 2a, and used in fluid flow simulations to give an accurate representation of the geology. Each element of the mesh can have discrete physical properties. Each lithology is a distinct hydro-stratigraphical unit, with identical porosity and conductivity values throughout. There are no barriers to flow between units.*

Graphical outputs visually illustrate the results of selected modelling experiments (Figs 3, 4). Each section mimics the stratigraphy, rock geometry and faults in the area. The different rock layers or faults are assigned different porosity and conductivity attributes, uniform to each rock type. Faults were treated by modelling artificially wide quadrilaterals, but with correspondingly reduced conductivity. Consequently, the measured area: conductivity relationship remains intact. For example, a real fault 10 m wide, 1 ma^{-1} conductivity, is modelled as 100 m wide, 10^{-1} ma^{-1} conductivity. BVG anisotropy (horizontal:vertical conductivity) was set at 5 for all experiments. Specific salinity values were taken from B/H 2 (saline 2%), and B/H 3 (brine 20%). These were entered as a linear vertical gradient of %NaCl.m^{-1} from a datum point measured in metres from the base of the section. To accommodate lateral variations of salinity, the code was modified to enable data files of salinities to be assigned to specific nodes on the finite element mesh. The overall salinity pattern was to mimic a 'pluton' of brine salinity in the lower left of the section, as derived from field measurements in B/H 3, 1, 10, 12, 5, 2, 4 (Nirex, 1992, 1993a). The groundwater directions are displayed by arrows, and it is important to note that fluid velocity is proportional to the length of the arrow of the fastest velocity on that particular plot, i.e. each different plot has a different arrow length scale. Crosses indicate that flow is less than 1% of the maximum for that plot, so that water could still be moving, but relatively slowly.

RESULTS: FLOW PATTERNS AND RATES

Calder Sandstone conductivity was

Table 1. Numerical values of hydraulic conductivity and porosity used during the modelling experiments for different rock units, taken from Nirex (1992, 1993a) Anisotropy values were chosen by us, with background information from Nirex. Measured conductivity units of ms^{-1} were converted to ma^{-1}, through multiplying 31×10^{6}. Permeability in milli Darcies shown to enable easy comparison with oil industry data sets (3.28 mD = approx. 1 ma^{-1}).

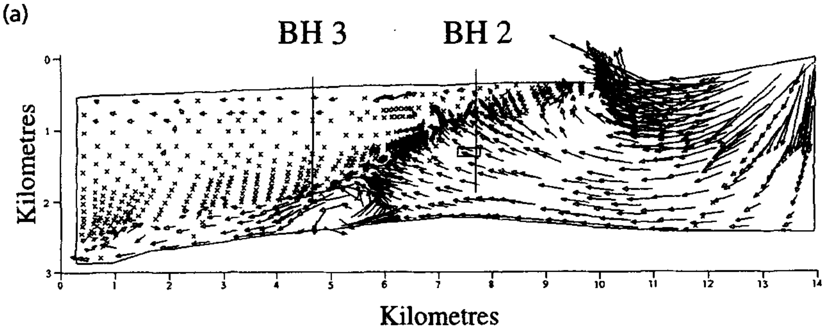
Stratigraphic Unit	Hydraulic Conductivity K (ma^{-1})	Intrinsic Permeability k(milli Darcies)	Porosity ϕ (%)	Anisotropy $(K_{horiz}/K_{vertical})$
Calder Sandstone	$3.0 \times 10^{+0} - 3.0 \times 10^{+2}$ (log mean) (log mean)	$1.0 \times 10^{+1} - 1.0 \times 10^{+3}$	20	10
St Bee's Sandstone	4.2×10^{-1} (log mean)	$1.4 \times 10^{+0}$	12	30
St Bee's Evaporites	1.6×10^{-3} (log mean)	5.2×10^{-3}	1	100
Brockram	9.46×10^{-4} (log mean)	3.1×10^{-3}	8	100
Carboniferous Limestone	1.5×10^{-1} (log mean)	4.9×10^{-1}	1	50
Borrowdale Volcanics	$1.2 \times 10^{-4} - 1.2 \times 10^{+0}$	$4.0 \times 10^{-4} - 4.0 \times 10^{+0}$	1	5
Faults in cover sequence	$3.0 \times 10^{+2}$ (log mean)	$1.0 \times 10^{+3}$	20	1
Faults in Borrowdale Volcanic Group	$1.2 \times 10^{+0}$	$4.0 \times 10^{+0}$	20	1

varied from $3.0 \times 10^{+1} - 3.0 \times 10^{+2}$ ma^{-1}, whilst keeping BVG conductivity constant. Flow rates in the sandstone related directly to conductivity, although patterns remained similar (Fig. 3a,b). Surprisingly, in each case, the flow through the Repository remained constant. This important result indicates that the Calder Sandstone and BVG aquifers are de-coupled.

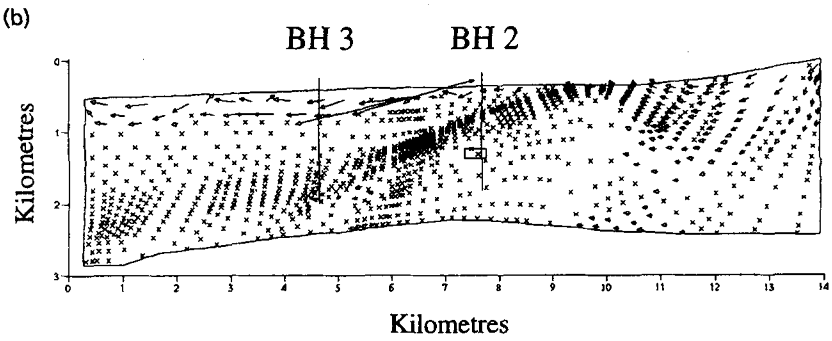
BVG conductivity was varied from $1.2 \times 10^{-5} - 1.2 \times 10^{+2}$ ma^{-1}, holding the Calder Sandstone conductivity constant for four cases from $3.0 \times 10^{+0} - 3.0 \times 10^{+2}$ ma^{-1}. In these 32 experiments, flow rate through the Repository is directly related to BVG conductivity. Absolute flow rate in the Calder Sandstone is not affected, but becomes visually less important on Fig. 4a,b. The pattern of flow direction remains similar in all cases, with upward flow at the 650–1000 m bOD depth proposed for the Repository, westwards horizontal flow beneath 1500 m, and westwards downwards flow in the BVG beneath the present coastline.

Our modelling suggests that, for any value of Calder Sandstone conductivity, flow through the Repository is unaffected. Thus the only contribution of this sandstone aquifer to Repository safety is the possible seaward transport and dispersion of any waters + radionuclides migrating upwards from the Repository through the BVG. Flow in the Repository relates directly to BVG conductivity, and the pattern of flow is persistently upwards, through several decade values of BVG conductivity experiments. These flow patterns imply that water from the Repository could eventually reach the surface as springs in the BVG outcrop, or by dispersion within the Calder Sandstone. Hence the proposed Repository position will need to engineer against natural groundwater flow, rather than be assisted by it.

The relationship of water flow to BVG conductivity can be expressed graphically. The results from 8 decades of BVG conductivity fall in a systematic pattern, with all Calder Sandstone conductivity results superimposed (Fig. 5). From this, we can make a simple safety case calculation. We assume that it is unacceptable for water from the Repository, 1000 m bOD, to return to the surface within 10, 000 years. Arithmetically, such a flow rate is 10^{-1} ma^{-1}. Using Fig. 5, this flow rate equates to a regional BVG conductivity of 3×10^{-2} ma^{-1}. If measured BVG conductivities exceed this value, then the hydrogeological safety of a 1000 m Repository must be doubted. Superimposed on Fig. 5 are the BVG conductivities measured by Nirex (1992, 1993a,b) in boreholes at 400–1900 m bOD. It is apparent that measured values are 40 times too large to be simply declared 'safe'. Only one connective fracture is needed to supply a radioactive warm spring to the surface, so that modelling the statistical distribution of fractures is unlikely to give sufficient confidence (Nirex 1993a). Further site investigation work needs to be directed towards establishing the long-term water flow rates in these locally measured fractures, so obtaining a more reliable assessment of regional BVG connectivity. Perhaps the most reliable way of achieving this confidence in engineering terms is to



Modelled flow through Repository = 1.1 ma^{-1}



Modelled flow through Repository = 1.1 ma^{-1}

▭ Proposed Repository Site
BH = Borehole

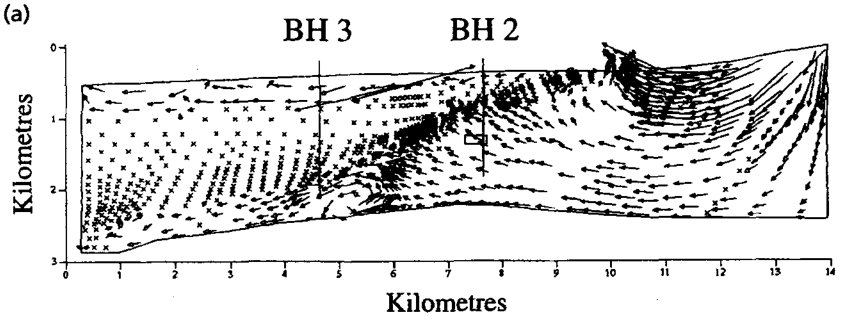
Fig. 3. *(a) Selected modelling experiment, to illustrate patterns of water flow directions. Calder Sandstone low conductivity (3* ma^{-1}*), BVG conductivity 1.2* ma^{-1}*. Flow through repository 1.1* ma^{-1}*. Repository shown at 1000 m, see text for explanation. (b) Selected modelling experiment, to illustrate patterns of water flow directions. Calder Sandstone high conductivity (300* ma^{-1}*), BVG conductivity 1.2* ma^{-1}*. Flow through repository 1.1* ma^{-1}*. Repository shown at 1000 m, see text for explanation.*

use boreholes to undertake *in-situ* flow tests, of many years duration, before any underground excavations are made to disturb the long-term flow pattern. Even so, this will only investigate the present-day conductivities and flows. This in itself gives no guide to the long-term forecasting of flow rates during future climate changes, or tectonically induced changes of conductivity. However, stable isotopic and noble gas data on present-day waters in these B/H (Nirex, 1993a) suggests that some BVG water may have recharged during a glaciation. This raises the possibility that the extra loading, topographical head and fracturing provided by an ice sheet could have induced much more rapid and extensive flows in the recent geological past, and could do so again in the geologically short-term future.

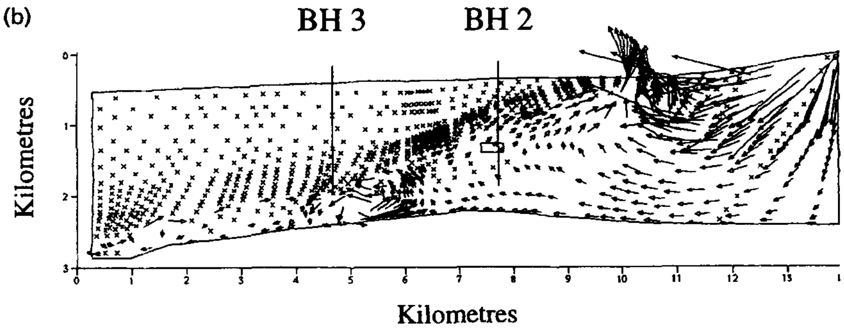
PARTICLE TRACKING

As a visual guide to the degree of physical containment that the BVG and overlying sediments may afford, we have undertaken a suite of particle tracking experiments (Figs 6, 7). We ignore any effects of enhanced flow due to thermal buoyancy of water from a warm Repository, or vertical leakoff of H_2, CH_4 and CO_2 gases generated from the Repository (Chapman, 1994). These particle tracking displays all assume that no chemical interaction of radionuclides with surrounding rock occurs, but simply monitor the progress of 'water particles' released from the Repository at an arbitrary Time = 0 (Garven, 1989). Such water could conceivably be carrying dissolved radionuclides. These particles have the same density and temperature as the surrounding water, so that they are passive indicators of water flow paths and dispersion, and do not have any inherent buoyancy or capillarity effects. These simulations have utilized two values of BVG regional conductivity of 1.2×10^{0} ma^{-1} and 1.2×10^{-2} ma^{-1} (3.8×10^{-8} and 3.8×10^{-10} ms^{-1}). These are about a factor of 10 above and below our own proposed 'safety target'. The upper value of BVG conductivity is the maximum measured value (Nirex, 1993a), the lower conductivity value is identical to the modal regional conductivity interpreted by Nirex (1993a,b) from their measurements and simulations. Fluid flow through porous media, or through fractures, usually moves preferentially along the highest conductivity conduits, rather than uniformly through the whole anisotropic medium. Consequently, our 'average' modelling will tend to under-estimate maximum flow rates. All other conditions are as for the experiment illustrated in Fig. 3a. The OILGEN code is run iteratively to achieve these tracking simulations, with a time step of just 3 years for each iteration. This ensures that a tracer particle does not jump between finite element cells. Five hundred tracking particles were 'released' at one time. Particle dispersion along aquifers was set to be 1 m laterally in 10 m forward flow, with 10% of this for transverse flow components.

Figure 6a and b show simulations with a Repository zone at 650 m (Nirex, 1993b; RWMAC 1994). It is apparent (Fig. 6a) that with high measured permeabilities, water from the Repository zone could reach the surface within 10, 000 years. Breakthrough of water from the BVG to overlying



Modelled flow through Repository = 1.1 ma^{-1}



Modelled flow through Repository = 19 ma^{-1}

▭ Proposed Repository Site
BH = Borehole

Fig. 4. *(a) Selected modelling experiment, to illustrate patterns of water flow directions. BVG conductivity (1.2 ma^{-1}), Calder Sandstone medium conductivity 30 ma^{-1}. Flow through repository 1.1 ma^{-1}. Repository shown at 1000 m, see text for explanation. (b) Selected modelling experiment, to illustrate patterns of water flow directions. BVG high conductivity (120 ma^{-1}), Calder Sandstone medium conductivity 30 ma^{-1}. Flow through repository 19 ma^{-1}. Repository shown at 1000 m, see text for explanation.*

sediments occurs predominantly via the Fleming Hall fault zone, but also via minor faults to its east. Breakthrough is very sensitive to the existence of such faults which focus flow, but not to their absolute values of conductivity. In Fig. 6b, it is apparent that a lower conductivity for the BVG has resulted in much longer containment of water. Repository water does not even leave the BVG until 50, 000 years after release (not shown), and takes 200, 000 years from its release until reaching the surface, having moved laterally through the St Bees Sandstone aquifer at 400 m depth then into the Calder Sandstone before discharging onto the present-day sea bed. Experiments in Fig. 7a, b investigate the potential benefit of placing the Repository deeper than currently proposed by Nirex, at 1000 m. With the high BVG conductivity, only a slight delay is found in the return of water towards the surface, with an arrival time of 15, 000 years (Fig. 7a), which is not very different to 10, 000 years in Fig. 6a. With the low BVG conductivity (Fig. 7b), flow from the Repository is much better contained, taking 300, 000 years to reach the surface after release. In this case, the water leaves the BVG slightly further west than Fig. 6b, but again flows laterally through the St Bees Sandstone some 400 m below the surface before discharging at the sea bed 4 km west of the experiment shown in Fig. 6b. From these experiments we conclude that both physical containment and discharge paths of water from the Repository are very sensitive to the conductivity of BVG rock surrounding the Repository. With the upper range of measured BVG permeabilities, any overlying sediments provide very little physical barrier or dispersion to flow. Once water from the Repository has entered the Calder Sandstone, dispersion ensures its transport to the surface. Other experiments (not shown) suggest that this is especially so with rapid lateral flows in the Sandstone. Thus the regional BVG conductivity is crucial. It is difficult to measure or estimate regional BVG conductivity in connected fractures with sufficient certainty (Nirex, 1993a). Consequently, at this Repository site, containment of radionuclides would need to be dependent upon the estimated certainty of chemical blocking from engineered barriers, or by chemical retardation from rock-water interaction. Any increase in BVG vertical conductivity either from engineering the Repository, or from gas leakoff from the waste (Chapman, 1994), would have a critically bad effect.

It is particularly instructive to contrast these deterministic results of our particle tracking experiments with the very different results obtained from Nirex's probabilistic modelling (RWMAC, 1994; Fig. 2). The Nirex model suggests that flow of water from the Repository will ascend into the fresh meteoric water in Carboniferous–Triassic sediments, and will then descend westwards into the higher density brines of the Irish Sea 'brine pluton'. Our modelling contradicts this. Different models with different assumptions produce different results, perhaps illustrating a lack of descriptive and predictive confidence.

CONCLUSIONS

1 Modelling experiments show that two decoupled, but connected, aquifer systems exist: in the Calder Sandstone

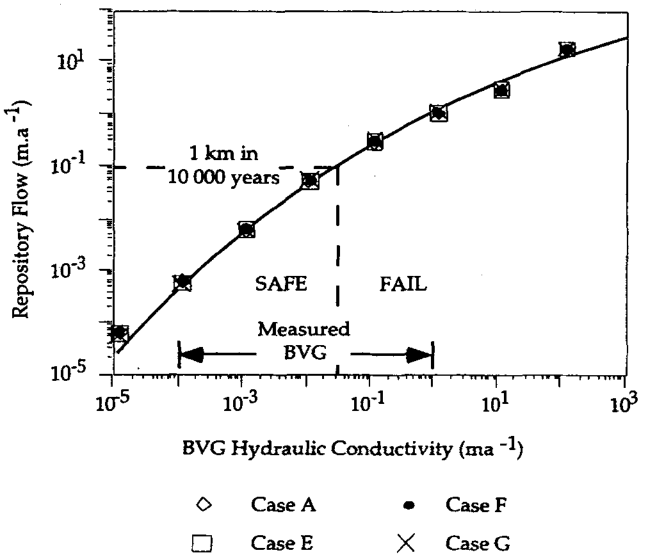
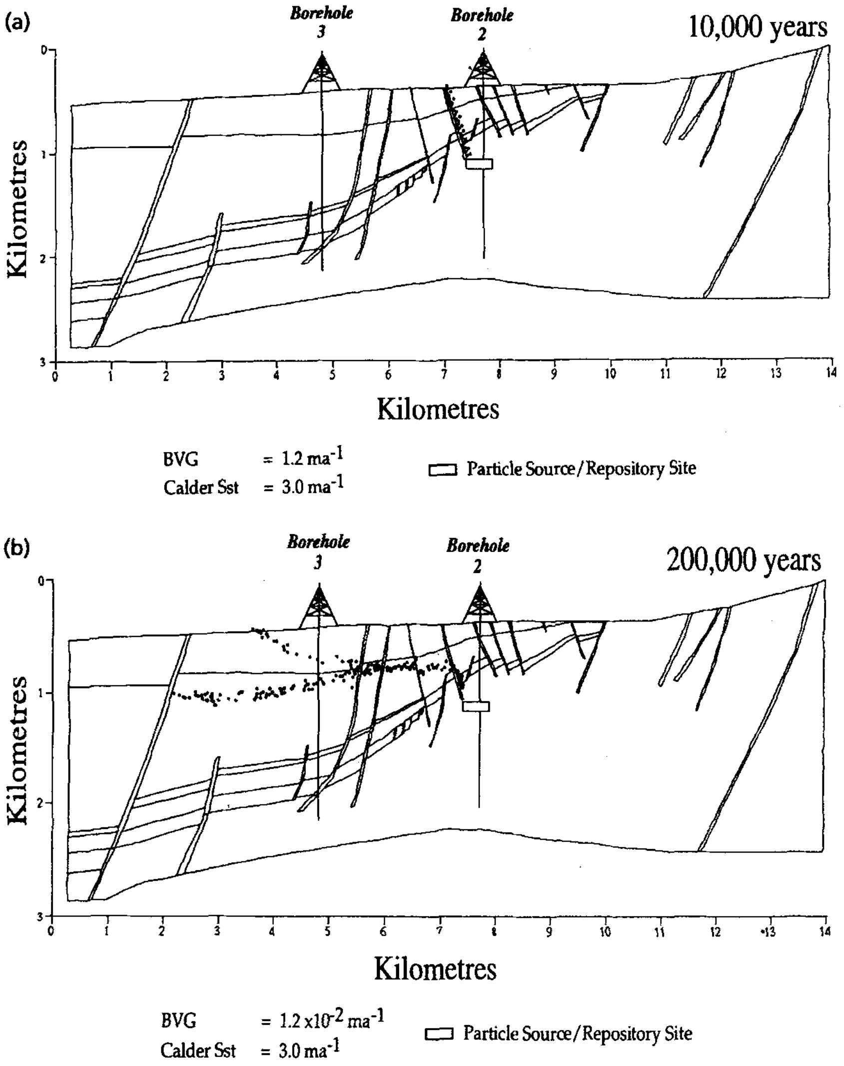


Fig. 5. *(left) Graph of Repository flow against BVG conductivity. This shows the range of values tested in 32 different experiments; the measured range of BVG conductivities was extended by* 10^{2} *upwards and* 10^{-1} *downwards, to give a greater context for interpretation. Varying the conductivity of the Calder Sandstone has no effect on flow through the Repository, and symbols for 4 different extreme cases (A–G) are superimposed. By contrast, variation in the BVG conductivity produces a very systematic change in modelled water flow through the Repository. A simple safety case has been superimposed, to assume that no water should return to the surface within 10, 000 yr. This would occur if flows were* 10^{-1} ma^{-1} *or faster (vertical axis). Using this model-derived graph, such flows would result if BVG conductivity was* 3×10^{-2} ma^{-1} *or greater* (1×10^{-9} ms^{-1})*. Some 35% of BVG fractures measured in Nirex boreholes at the proposed Repository depth of 650 m exceed this conductivity (Nirex, 1992, 1993a, b). Thus the measured range of fracture conductivities, superimposed on the horizontal axis, mainly fall in the 'Safe' sector, but 35% of fractures fall in the 'Fail' sector, and are up to 40 times too permeable.*

Fig. 6. *(right) (a) Particle tracking diagram showing positions of water tracked from the 650 m deep Repository. BVG conductivity is the maximum measured in site investigation boreholes, 1.2* ma^{-1} (3.8×10^{-8} ms^{-1})*. The Calder Sandstone set to low conductivity, 3* ma^{-1}*. Water from the Repository reaches the surface by 10, 000 yr after release, and 50% of particles released reach the surface by 30, 000 yr. Experiments not shown indicate that increasing the conductivity of the Calder Sandstone to 30 or 300* ma^{-1} *reduces the time for particles to reach the surface. (b) Particle tracking diagram showing positions of water tracked from a 650 m Repository. Conditions as for Fig. 6a, but BVG conductivity reduced to* 1.2×10^{-2} ma^{-1} (3.8×10^{-10} ms^{-1})*. This is the modal value proposed by Nirex (1993a), but some 40% of all BVG measured fractures exceed this (Nirex 1993b, fig. 10a). This produces a marked difference from Fig. 6a, water from the Repository is still within the BVG 50, 000 yr after release, and does not reach the sea bed until 200, 000 yr after release.*



and in the Borrowdale Volcanic Group. Modelled flow rates within the BVG are directly dependent on BVG conductivity. Flow conductivities measured in boreholes are 40 × too great to be acceptable.

2 The proposed repository at 650–1000 m is in a poor position where flow directions in the BVG are towards the surface, and will need to be

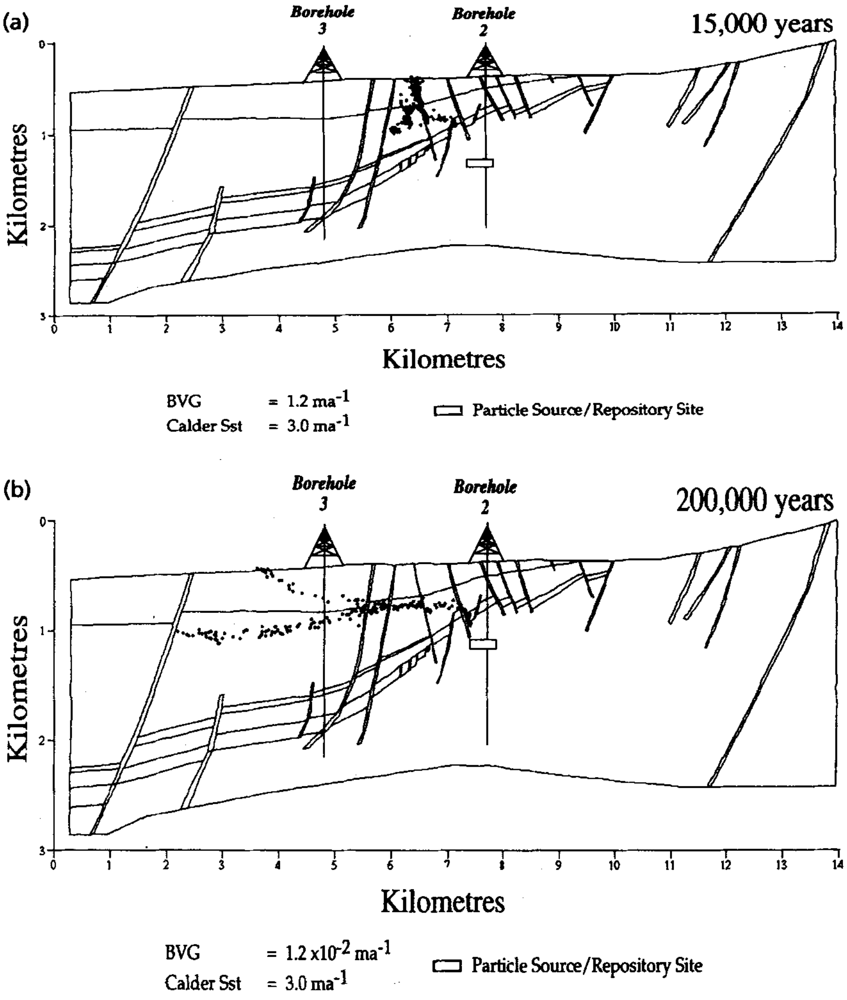


Fig. 7. *(a) Particle tacking diagram showing positions of water tracked from a putative 1000 m Repository. All other conditions as Fig. 6a. Water from the Repository Zone has reached the surface after 15, 000 yr, and 50% of particles released reach the surface by 30, 000 yr. Simply placing the Repository deeper in permeable BVG rock does not help. (b) Particle tracking diagram showing positions of water tracked from a putative 1000 m deep Repository. All other conditions as Fig. 6b, i.e. BVG conductivity 1.2 × 10^{-2} ma^{-1} (3.8 × 10^{-10} ms^{-1}). Results are similar to Fig. 6b. In this case water from the Repository Zone does not reach the surface until about 300, 000 yr after release. Another major difference is that water leaves the BVG slightly further west, again moving horizontally through the St Bees Sandstone some 400 m beneath the surface and up to the sea bed. Thus it is critical to demonstrate that all present and future regional conductivity in the BVG is substantially less than 3 × 10^{-2} ma^{-1} (Fig. 5).*

counteracted. Better sites for a Repository would seek positions where water flow directions are downwards, seawards, or static, such as 2000 m beneath the present coastline. However, engineering costs may be prohibitive.

3 Simulated tracking of water particles released from the Repository zone shows that radionuclides could return to the surface within 10, 000–30, 000 years, if regional conductivity of the BVG was equivalent to its highest measured value of 1.2 ma^{-1}. We assume that no chemical retardation occurs within the engineered Repository, or within the overlying rock.

4 Further site investigation work must establish that *all* BVG fractures have a large-scale regional conductivity *less than* 3 × 10^{-2} ma^{-1}. The most direct way of measuring this is by water flow tests in boreholes, lasting many years, before any excavations are made. Consideration should be given to climatically induced changes in subsurface conductivity and water flow patterns from the past, and in the future.

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