

HIGH-ISOLATION SITES FOR RADIOACTIVE WASTE DISPOSAL: A FRESH LOOK AT THE CHALLENGE OF LOCATING SAFE SITES FOR RADIOACTIVE REPOSITORIES.

I. Miller, J. Black, C. McCombie, D. Pentz, P. Zuidema

ABSTRACT

This paper presents the technical case for a class of "high isolation sites" suitable for disposal facilities for long-lived radioactive waste. Instead of all countries pursuing independent, complex, and expensive programs to develop national repositories, it is proposed to investigate the potential for implementation of multinational repositories based on superior sites chosen primarily for geologic reasons, independent of national borders. These sites can provide great natural waste isolation, can be developed efficiently, and may lead to increased public confidence in the safety of disposal.

Based on a review of factors favorable for site safety, and of other suitability criteria, the paper develops a description of the class of high isolation sites with an accompanying list of characteristics or signatures of such sites.

The paper presents a summary of performance assessment considerations for high isolation sites. When compared to more conventional sites, performance assessment for high isolation sites will focus more on confirming the presence and stability of the processes preventing waste migration. The lower driving forces for flow and transport should ease requirements for quantifying pathway directions, transport mechanisms, and ultimately mass flux rates and doses to receptors.

The paper concludes with a summary of the proposed stages involved in selecting and characterizing such a high isolation site. Because these sites rely primarily on geological processes for long-term waste containment, site characterization will focus on confirming the presence of the signature features, and on direct evidence of long residence-times for deep groundwater at the site.

INTRODUCTION: THE CONCEPT OF GEOLOGIC DISPOSAL

For some types of radioactive wastes, the arguments in favor of deep geologic disposal concepts are evident to any technically-oriented person. High-level wastes and long-lived wastes have hazardous lifetimes which - although not infinite, as for some chemo-toxic wastes - are nevertheless enormously long compared to any time scales which man has as yet considered when seeking solutions to technological problems. There is obviously no experience with the behavior of technical systems over hundreds of thousands of years. Where do we have natural systems with such time constants? Today, the only accessible locations lie deep below the land or

ocean surfaces of our earth, since the advanced technology required for extra-terrestrial disposal is excluded on grounds of reliability and costs.

The concept of deep geological disposal was therefore proposed some decades ago (1). The concept is a logical consequence of the easily observable decay of radioactivity with time which leads to a continuous reduction in toxicity of these wastes. It is not (despite the view held today by many opponents) a "cheap and nasty" solution, justified by an "out-of-sight, out-of-mind" philosophy. Indeed, the technology of deep disposal is expensive and can be economically justified only because the amounts of long-lived wastes produced in the nuclear fuel cycle are small in relation to the vast reserves of energy released in the fission process.

Finite hazardous lifetimes (and low volumes) led to the development of concepts where environmental protection could be aimed at by **isolating wastes** from man's surroundings for long enough to allow radioactive decay to occur. This led in turn to the search for environments that show **sufficient stability** for the time periods involved, i.e. it led to the concept of geologic disposal.

Over the past decades, huge efforts have been invested by national programs and in international co-operation projects to bring the geologic disposal concept to maturity. In this time, significant progress has been made and technical approaches have been adapted to take account of lessons learned. In particular, early concepts based almost purely on retention of radionuclides by the geologic media have been overtaken by repository system designs which use both engineered and natural barriers to assure safety. The increased importance of engineered barriers such as high integrity containers with expected lifetimes of tens of thousands of years, is justified because:

- They provide more defense in depth (a diversity of safety barriers for guarding against the diverse processes which could lead to radionuclide releases)
- They allow increased assurance of safety for the first thousands of years – although the geologic setting must still provide the long-term safety barrier.

The relative weight placed upon the various safety barriers reflects the technical design choices made, the expected geological conditions, and – very importantly - the level of confidence placed by the repository implementer in its ability to adequately characterize the long-term performance of individual components of the system. For example, an interesting cross-comparison for HLW disposal projects is presented in Neall et al (2) in which it is pointed out that the current Swedish concept emphasizes their long-lived copper canister, the Canadian concept their very high quality crystalline rock, and the Swiss safety concept the stable near-field geochemistry. In the USA, the disposal concept at Yucca Mountain has evolved from near complete reliance on the geology to heavy dependence on engineered barriers such as the fuel cladding and the overpacks.

The important messages with respect to system design that can be learned from this experience are that:

- Various combinations of engineered and natural safety barriers appear to be capable of providing adequate levels of repository safety.

- There is no "safest" choice for any particular system component (including host rock or site).
- The most important requirement is a robust system design and robust safety analyses which give confidence that required safety levels can be met.
- The confidence in our ability to analyze long-term performance depends on our level of understanding of the physical, chemical and geological processes involved.
- The increased importance of engineered barriers is in part a reaction to the increasing awareness of the difficulties in characterizing complex geologic systems with the resolution and the accuracy required for repository analyses.

CURRENT TRENDS IN NATIONAL PROGRAMMES

Today, there are no deep geologic repositories in operation. In fact, not only are no deep geologic repositories operating, but no specific site (with the exception of the WIPP in the USA) has even been confirmed as suitable. A single, preferred site has been proposed in some countries, for example in Germany at Gorleben, in the USA at Yucca Mountain, in Belgium at Mol and in the United Kingdom at Sellafield. For HLW disposal in Sweden, Finland, France and Switzerland, more than one siting option will be kept open for the next several years. In countries like Japan and Canada, the transition from generic to site-specific repository projects has not yet been made.

In all of these countries, however (indeed in all nations with the exception of the Netherlands) a commitment has been made to a geologic repository as a solution for disposal. The basic feasibility of the approach is accepted within the waste management community; and the achievability of safe disposal has been asserted by innumerable panels of international experts. In all states with nuclear activities, active programs for repository development are underway and no insuperable technical problems are foreseen by those directly responsible or, indeed by the majority of the scientific / technical community.

In wider public and political circles, however, perceptions are often different. Waste disposal programs are not widely regarded as being on a straightforward – if slow – route towards successful implementation. Rather the process is often seen as fragile, faltering or even failed. In recent years there has, therefore, been growing support for other approaches such as long-term surface storage or advanced transmutation schemes – although neither of these can be regarded as a real alternative to deep disposal.

The single most important reason for this is the lack of public confidence in the ability of scientists to predict repository performance with sufficient reliability over the long time scales of relevance. Methodologies have been developed by the experts to at least scope the bounding behavior of disposal systems. However, safety assessments for deep repositories have become enormously complex (eg., 3) and are dependent on assembling huge site databases which are expensive, difficult to quality-assure and still open to criticism for their potential omissions or errors. Within the technical area, the issue which has undoubtedly led to the most debate is the characterization of the deep geologic environment at a potential repository site. Because the

geologic media being studied are mostly complex and heterogeneous on the scales of relevance, this has turned out to be a much more challenging task than was appreciated in early years.

RETHINKING THE GEOLOGIC DISPOSAL CONCEPT

The thrust of this paper is a proposal to step back and review how the task of geologic disposal might be eased. The proposed approach taken is purely technical in its initial stages; i.e. the emphasis is on aspects of deep disposal which are relevant to safety. Other important areas such as engineering feasibility, economics etc. are touched upon in a companion paper at this Conference (4). The siting issues with perhaps the greatest challenge of all are of course public and political communication and co-operation. These are not discussed in the present paper, although we are well aware that consensus amongst all stakeholders, including the host communities, will be an even greater issue for multinational projects.

Over the past twenty years, great progress has been made in improving the scientific understanding of geologic disposal (5). In some senses, it is this increased scientific understanding that has caused the problems that have afflicted repository programs, as simplistic early concepts have given way to more complex ones. However, the improved understanding can be used positively to derive from scientific/technical reasoning a list of preferred characteristics for disposal sites.

From the safety perspective, it makes sense to look for such sites world-wide, with no constraints of national boundaries. Transport of radioactive wastes, although a sensitive public issue, should not present an insurmountable obstacle to the project. The safety record for the transport of nuclear material has been excellent with no instance of significant radioactive releases in many millions of transport miles.

In the following sections we analyze the technical requirements for better sites, and then go on to develop a 'signature' for such sites. This is followed by a discussion of how the safety case would be made for these sites, and finally a discussion of the site selection process involved.

HIGH-ISOLATION SITES: A TECHNICAL DERIVATION OF PREFERRED CHARACTERISTICS

Based on their own experience, and on a review of the problems which have beset many national repository siting programs, the authors propose that the following list of seven key technical (long-term safety related) siting factors are central to the repository siting process:

1. Advective Groundwater Transport

This is normally the most important release mechanism, which dominates the isolation capability of proposed sites. When advective transport is minimal, and diffusive processes dominate, the eventual transport of radionuclides away from a repository will

be extremely slow, and transit times will be so long that most radionuclides will decay within the repository or the host geological formation. Figure 1 shows the improvement in a site's ability to retain wastes as a function of the amount of advective groundwater flow through the host rock.

2. Direct Exposure of Waste at the Ground Surface

Whether through erosion or uplift, a successful site must have no mechanisms capable of directly exposing wastes at the ground surface over periods of up to a million or more years.

3. Other Transport Mechanisms: Human Intrusion, Biotic, Tectonic

All other credible mechanisms for moving emplaced wastes to the biosphere must also be shown to be insignificant threats. These include inadvertent human intrusion (e.g. due to mineral exploration), tectonic processes (earthquakes, vulcanism), and even highly-unlikely processes such as biotic transport mechanisms (e.g. plant or animal intrusion, microbially-enhanced transport).

4. The Biosphere

Regardless of the quality of the geological barrier, it is desirable to site a repository in a location where any eventual releases of radioactivity would have minimal impact on human or ecological receptors. Given the extremely long times before any release is conceivable, it will be problematic for most potential repository locations to describe the future biosphere conditions with much certainty.

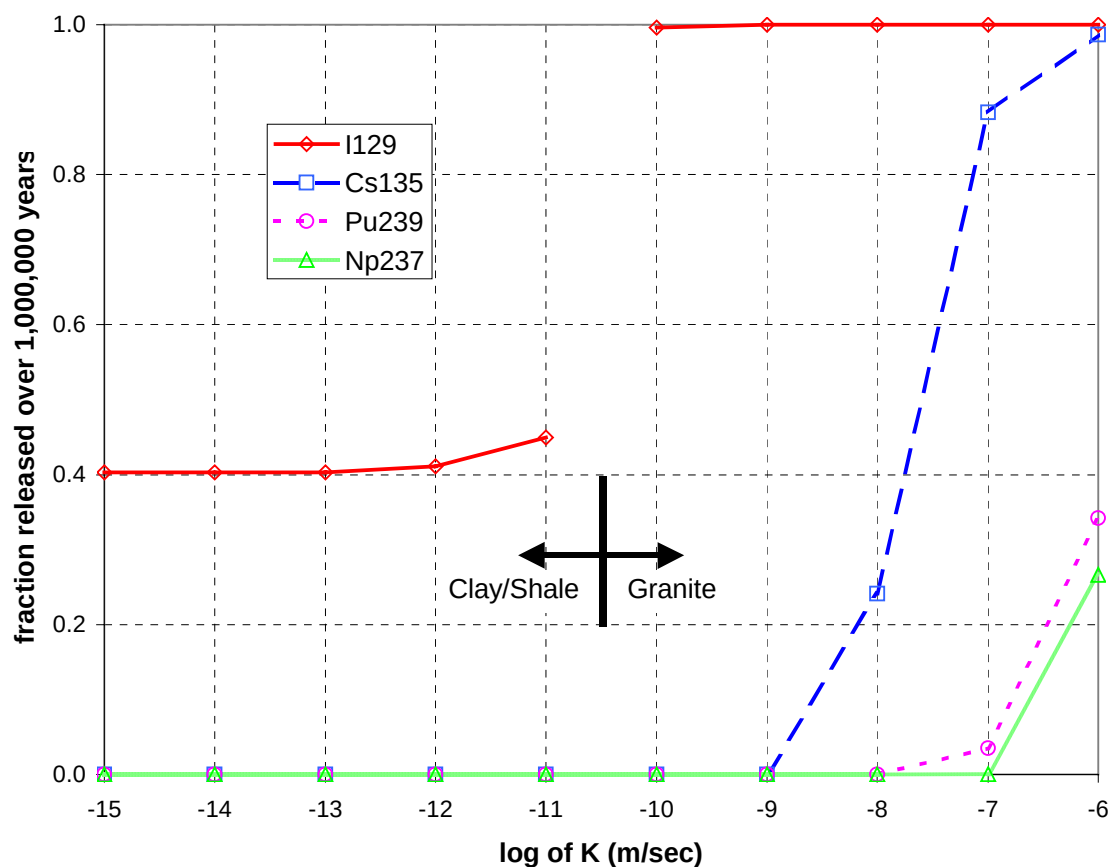


Figure 1. Significance of Advective Flow Rate

Figure 1 shows for some key nuclides what fraction of the inventory emplaced into a repository beneath a 100m thick rock layer would escape to the surface in a million years. The inventory is representative of typical spent fuel.

The analysis assumed there was no engineered barrier at all, and that the waste form did not protect the waste from dissolution. An upward hydraulic gradient of 0.01 was assumed. Representative properties were assigned to a clay/shale and a granite type of host rock. Solubility limits prevented excessive concentrations of the nuclides in the repository.

For the clay/shale, transport is primarily by diffusion through the rock matrix, which has a relatively high porosity. For the granite, transport is entirely by advection through fractures, with retardation due to the process of matrix diffusion. As can be seen, the diffusion-dominated systems prevent any release of the retarded nuclides. They also ensure that for unretarded nuclides, the release rate is very slow, and there is no release at all for several hundred thousand years.

5. The Extremely Long Times Which Must Be Considered

Repository safety analyses are routinely carried out for a million or more years into the future. These time scales challenge the conventional basis for the design of novel technological systems. Designs for such systems are usually based on a combination of past experience and theoretical projections which can be supported by testing and observations of performance on relevant time scales. Because it is not possible to test and observe the engineered components of a repository over representative time scales, a repository's safety should ideally be guaranteed by natural processes which have already demonstrated their performance over millions of years.

6. Confidence In / Reliability of Projected Behavior

In general, repositories are held to stringent safety standards which are often even stricter than those applied to existing nuclear facilities. These standards require nearly perfect containment of the emplaced wastes, as even a small fraction returning to the biosphere can result in violating the standards. Moreover, it must be demonstrated that they will continue to meet these standards for an extremely long time. This will require developing an unprecedented level of confidence in our ability to understand the long-term future performance of the repository system.

7. Time and Effort Needed to Assemble an Adequate Site Database

With the growing awareness of the complexity in structure and processes that typically exists in geological systems, the time and effort involved in characterizing potential repository sites has far exceeded early estimates. Arguably, some potentially safe sites could never be licensed due to the excessive costs that would be required to adequately characterize them. Today, the value of choosing and designing repository systems which lend themselves to simpler analyses is increasingly recognized.

Each of the seven factors described above is sensitive to the characteristics of the repository site. It is possible to go through each factor in turn, and identify favorable site characteristics for addressing that factor. Table I presents a set of favorable characteristics associated with each factor.

Table I Identification of Favorable Siting Characteristics

Goal	Site Characteristic
Factor: Advective Groundwater Transport	
<u>Minimizing moving groundwater</u> Low hydraulic gradients Low permeability Low water quantities Lack of other hydraulic driving forces	Flat site topography Clay/shale sedimentary units Low rainfall, low infiltration Increasing salinity with depth (has positive stability)
<u>Minimizing releases from waste packages</u> Low corrosion rates Low solubilities	Reducing groundwater Reducing groundwater
<u>Enhancing retardation in geosphere</u> Long horizontal flow-paths, large vertical diffusion distances High sorption	Long time/distance to exfiltration areas Clay/shale sedimentary units, not fracture-dominated
Factor: Direct Exposure of Waste at the Ground Surface	
Minimal orogenic uplift Minimal erosion	Tectonically stable region Flat site topography, tectonically stable, arid climate, no glaciation
Factor: Other Transport Mechanisms: Human Intrusion, Biotic, Tectonic	
Mining Boreholes, including wells Biotic intrusion Tectonic disruption	Minimal mineral potential Low permeability, saline groundwater Sufficient depth Tectonically stable region
Factor: Biosphere	
Low population density Minimal ecosystems Minimal agricultural capability	Arid, remote, saline groundwater Arid, saline groundwater Arid, saline groundwater
Factor: Extremely Long Times Frames Considered	
EBS lifetime $10^3 - 10^4$ of years Geological processes $10^5 - 10^6$ years	Stable host rocks, low permeability, stable hydrogeochemistry Tectonically stable region, stable climate
Factor: Confidence In / Reliability of Projected Behavior	
Independent indicators Lack of structural complexity	Old groundwater Uniform, horizontal, simple geological structures
Factor: Time and Effort Needed to Assemble Site Database	
Homogeneity, extrapolability, simple processes	Uniform, horizontal, simple geological structures

The site characteristics identified in the right-hand column of Table I tend to be repetitive, and when combined they define a set of signature characteristics for high isolation sites for radioactive waste disposal. Table II summarizes this set of favorable characteristics considered ideal for high-isolation sites. While all of the characteristics are desirable, those characteristics that are considered essential are shown in bold. Some of the characteristics can be demonstrated only by specific field investigations at a site. Others can, however, be judged at a broad screening level using generally available data.

Table II High Isolation Site Signature

	Signature Description	Purpose
1	Stable geology, with minimal tectonic or volcanic activity.	Protects the repository system from disruption over the very long periods considered.
2	Very flat topography with minimal relief.	Minimizes groundwater gradients and flow velocities.
3	Extensive near-horizontal, layered (sedimentary) geologic strata.	Simple, predictable geology is easier to characterize; layering makes vertical transport of dissolved radionuclides less likely (anisotropy). Sediments generally provide good chemical retardation. Some of the most toxic radionuclides are also the most highly retarded, traveling much more slowly than the groundwater that carries them
4	Stable arid climate, not susceptible to glaciation.	Enhances temporal predictability of biosphere conditions. Minimizes groundwater flow due to minimal recharge of precipitation; absence of glaciation protects against erosional or rock mechanical or hydrogeological perturbing effects of glaciers.
5	Low permeability, homogeneous rock in the repository host formation.	Minimizes opportunity for rapid advective releases of radionuclides dissolved in flowing groundwater.
6	Host formation thickness of 100m or more.	Even with no groundwater flow, releases can in principle take place by diffusion in stagnant pore water. This thickness easily provides a sufficient barrier to diffusion-dominated radionuclide release.
7	Very old groundwater in the host formation.	Proves that the repository is isolated from the surface, demonstrating that minimal advective flows are occurring.
8	Repository system not susceptible to disruption from erosion.	Protects the repository system from disruption.
9	Saline, non-potable groundwater of limited use for drinking or agriculture; no extensive aquifers.	Minimizes the risk of future site inhabitants being exposed to any eventual radionuclide releases.
10	Vertical salinity stratification of ground water.	A highly favorable attribute which, if it exists, may make it impossible for deeper groundwaters to move up from the repository horizon to the surface.
11	Stable, reducing geochemical environment in the host formation.	Enhances system performance through lower solubilities of many radionuclides, and through lower corrosion rates.
12	No major karstic formations at the site.	Flow pathways in karsts (partially-dissolved limestones) are difficult to characterize and predict.

MAKING THE SAFETY CASE

As for any repository, the planning and implementation of a high-isolation repository will proceed in a step-wise manner, requiring a number of interdependent decisions to be taken regarding siting and design, site characterization and, eventually, licensing. For many (but not necessarily all) decisions, a case for long-term safety will be an important part of the information on which the decision will be based.

The safety case must give confidence in the robustness of the site and design, i.e. it must show that the selected site and design are favorable to safety and that residual uncertainties in the analyses can not have an unacceptable detrimental effect on safety. The safety provided by the site and design must be shown transparently using methods, models and data in whose reliability there exists technical consensus and public confidence. The methods, models and data should take full account of phenomena that are relevant to long-term safety, including uncertainty in these phenomena, so that performance is evaluated in a manner that can not underestimate consequences. However, the analyses should avoid excessive simplification or over-conservatism. Thus, in principle, the safety assessment for a high-isolation site will not differ from safety assessments as produced in other repository programs.

In practice, the high isolation concept is aimed at easing the burden of a safety proof by choosing a system with as many positive safety characteristics as is feasible. The proposal aims at providing a site and design that are of intrinsic high quality with respect to safety and are also amenable to a reliable assessment of safety. Containment of the waste, and retention of any releases, will be achieved through the operation of multiple, interdependent processes (the multi-barrier – or better, "multi-phenomena" concept). Sealed containers will provide complete containment for a period long enough for many of the most radiotoxic nuclides to decay. Furthermore, siting and design will ensure that radionuclide transport processes are very slow, that uncertainties in the information base are minimized (e.g. through the choice of a structurally simple site) and that the safety-relevant phenomena are sufficiently well understood that their effects can be reliably bounded.

In detail, the safety case for a high-isolation site may be different from that for more conventional sites because of the low energy natural system, which has extremely low driving forces for any processes which could lead to nuclide release and transport. This should make it easier to deal with groundwater flow scenarios of the types that are central to most conventional safety assessments. Direct evidence of extremely long residence times (e.g. by age dating, salinity profiling) will be an important goal. Because of the expected near stagnant groundwaters, however, the safety case may have to focus more upon potential disturbances of the natural system due to artifacts introduced by the repository itself.

There will, nevertheless, remain uncertainties in the description of some safety-relevant phenomena. Safety assessments performed throughout the course of planning and implementation should be used to identify these uncertainties. They should also focus site characterization and R&D activities in order to ensure that any uncertainties with the potential to undermine the safety case are dealt with. The objective is to either reduce the

uncertainties themselves or, by appropriate design changes, to reduce their impact on the performance of the proposed repository.

SITING A HIGH ISOLATION REPOSITORY

The high isolation site signature presented in Table II lends itself to a focussed siting process. Starting from a global review, such a process moves to successively smaller regions. Obviously, however, the siting requirements must incorporate socio-political and technical-feasibility factors along with the seven safety-relevant technical factors discussed above. The more extensive the regions which fulfil the technical criteria, the more flexibility one has in selecting potential sites satisfying the other criteria also.

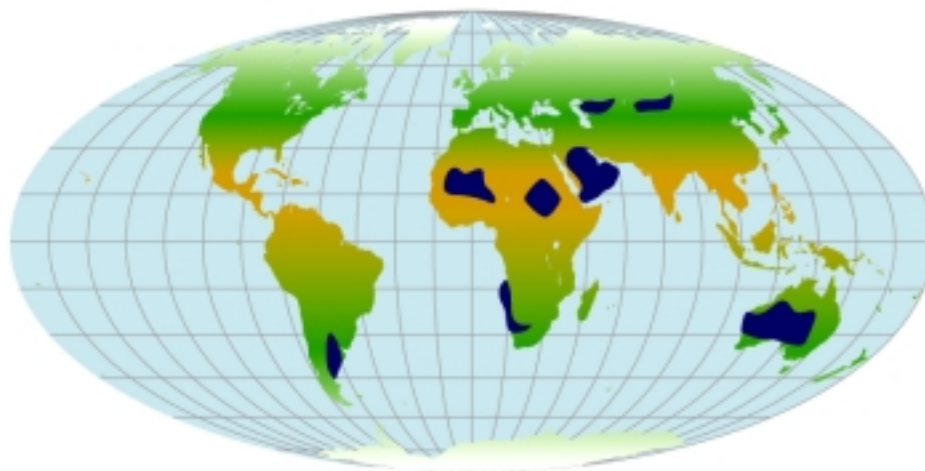
A study of the world map aimed at identifying large, flat, historically-arid areas with stable and simple geologic formations quickly leads to a group of areas which were part of the original Pangea continental mass which started to break apart some 80 million years ago. Figure 2 shows that these areas, which have been subjected neither to large tectonic forces nor to the influences of repeated glaciation, are primarily in the Southern Hemisphere. The largest contiguous stretch is in the desert basins of Western and South Australia.

Table III presents a sequential process for identifying candidate regions, sub-regions, and eventually sites starting from the large areas described above. Because of the signature requirement for near-horizontal, layered sedimentary strata, the uniformity of the areas lends itself to an efficient siting process, and results from exploratory programs can be extrapolated for considerable distances. Additionally, all of the signatures in Table II can be readily measured, and many of them are already available from public climatic and geological records. Lastly, many of the signatures are correlated, such that the presence of the more readily observed signatures will provide increased confidence that the signatures that require intrusive testing, such as old and saline groundwaters, will be present.

Although the emphasis in this paper is on technical aspects of site selection, other socio-economic factors are also included (although not in a comprehensive manner) in order to reflect the high importance of simultaneously considering all relevant issues.



Pangaea Supercontinent – 200 million years ago



Potential Signature Areas – Present Day

- Composite of:
- Quaternary Aridity
 - Low Population
 - Low-sloping Topography
 - Low Seismicity - Stable Tectonics

Figure 2 Global Screening for Suitable Areas

Table III Siting Stages

STAGE	KEY SIGNATURES	SELECTION PROCEDURE
1. Global Areas	• Stable geology, with minimal tectonic or volcanic activity. • Very flat topography with minimal relief. • Stable arid climate, not susceptible to glaciation. Continent or country should be stable politically, and be technically advanced,	• Study of world geology, continental evolution. • Regional maps. • Regional maps. • Stable democratic society, knowledge of nuclear issues
2. Regions (100 - 1,000km)	• Extensive near-horizontal, layered geologic strata. • Very flat topography with minimal relief. • Saline, non-potable groundwater.	• Exclude extensive aquifers. • Exclude vicinity of “rainy”, mountainous regions • (see all of Table II)
3. Sub-regions (20 – 100km)	• Should be geologically simple so that exploratory boreholes represent large areas, • If multiple sub-regions are considered, they should have diverse geological environments, • Avoid obvious local political problems, • Be optimized for cost and time.	• Avoid local manifestations of the exclusion criteria of Table II, • Optimize land ownership, overall infrastructure requirements.
4. Specific potential sites (10km)	• Should have identified suitable host rock, • Should have readily understood and demonstrably good geosphere • No insurmountable societal conflicts.	• Same as above: - plus: • Geological and hydrogeological information from boreholes (i.e. groundwater ages, salinity profiles, etc). • Check ownership, negotiate compensation schemes etc.
5. Site characterization at preferred site	• Site should appear intrinsically safe, • Should be economically constructable,(suitable rock, infrastructure etc.) • Should be politically approved.	• Affirm on basis of Performance Assessment, cost and political acceptability.

SUMMARY

World-wide progress to date in developing geological repositories for the disposal of spent fuel and high level waste is not encouraging. By taking a fresh look at the reasons for the difficulties which have faced most national repository programs, and discarding the preconception that each country must develop its own disposal facilities, it is possible to define a class of simple, superior high isolation sites which may provide a multi-national basis for solving the nuclear waste disposal problem. The relatively small volumes of HLW or spent fuel which arise from nuclear power production make shared repositories a feasible proposition. For small countries, the economies of scale which can be achieved make the concept attractive. For all countries, objective consideration of the relative merits of national and multi-national solutions is a prudent part of planning the management of long-lived radioactive wastes.

AUTHORS

Ian Miller,	Golder Associates Inc., Redmond, Washington USA.
John Black	Golder Associates UK Limited, Nottingham, England
Charles McCombie	Pangea Resources Australia Pty Ltd.
David Pentz	Pangea Resources Australia Pty Ltd.
Piet Zuidema	Nagra, Baden, Switzerland

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