SANDIA REPORT
SAND2006-3570
Unlimited Release
Printed September 2006

Preliminary Study on Hydrogeology in Tectonically Active Areas

Thomas S. Lowry, Scott C. James, Richard M. Jensen, Moo Y. Lee, Allen R. Lappin,
Bill W. Arnold, Glen L. Gettemy, and Diane K. Meier

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of Energy's
National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2006-3570
Unlimited Release
Printed September 2006

Preliminary Study on Hydrogeology in Tectonically Active Areas

Thomas S. Lowry, Scott C. James, Richard M. Jensen,
Moo Y. Lee, Allen R. Lappin, Bill W. Arnold,
Glen L. Gettemy, and Diane K. Meier
Geohydrology Department, 06115
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0735

This project was funded by the Nuclear Waste Management Organization of Japan (NUMO), under a Department of Energy, Work For Others, Funds-in Agreement, contract No. FI 061051107, entitled "Preliminary Study on Hydrogeology in Tectonically Active Areas". All work was performed and completed at Sandia National Laboratories, Albuquerque, New Mexico, USA.

Abstract

This report represents the final product of a background literature review conducted for the Nuclear Waste Management Organization of Japan (NUMO) by Sandia National Laboratories, Albuquerque, New Mexico, USA. Internationally, research of hydrological and transport processes in the context of high level waste (HLW) repository performance, has been extensive. However, most of these studies have been conducted for sites that are within tectonically stable regions. Therefore, in support of NUMO's goal of selecting a site for a HLW repository, this literature review has been conducted to assess the applicability of the output from some of these studies to the geological environment in Japan. Specifically, this review consists of two main tasks. The first was to review the major documents of the main HLW repository programs around the world to identify the most important hydrologic and transport parameters and processes relevant in each of these programs. The review was to assess the relative importance of processes and measured parameters to site characterization by interpretation of existing sensitivity analyses and expert judgment in these documents. The second task was to convene a workshop to discuss the findings of Task 1 and to prioritize hydrologic and transport parameters in the context of the geology of Japan. This report details the results and conclusions of both of these Tasks.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 Introduction and Background

This report represents the final product of a background literature review conducted for the Nuclear Waste Management Organization of Japan (NUMO) by Sandia National Laboratories, Albuquerque, New Mexico, USA.

In accordance with the NUMO site selection program (NUMO, 2004), selection of preliminary investigation areas (PIA's) are to be conducted using a stepwise application that involves siting factors that are placed into two main groups: Evaluation Factors for Qualification (EFQ) and Favorable Factors (FF). EFQ's concern the stability of a site with regard to potentially disruptive events such as seismicity and/or volcanism. FF's on the other hand, take into account a wide range of geological, environmental, social, and economic characteristics. The EFQ's consist of absolute requirements that would eliminate a site based on certain criteria (e.g. its proximity to a volcano and/or fault). Conversely, the FF's are expressed as a list of preferences that can be compared and contrasted in a flexible manner to assess the advantages and disadvantages of a particular site.

The Japanese Islands lie in a belt of active tectonics with high frequencies of earthquakes, faults, volcanoes, uplift, and subsidence. The evaluation methodology for long-term stability of candidate areas for a high-level waste (HLW) repository is a fundamental issue, and has been discussed in several research and development (R&D) programs in NUMO, such as the International Tectonics Meeting (ITM). After applying the tectonic site selection factors, hydrological and radionuclide transport characteristics will be used to help screen for PIA's. While not explicitly detailed in the EFQ's, hydrology is implicitly present due to its inter-connection with local tectonic phenomenon (Figure 1).

Determination of the hydrologic and transport processes that are of importance at a site will be a difficult job in that this determination needs to account for the possibility of tectonic processes altering the geohydrology, geochemistry, and transport characteristics over time. Additionally, site-specific data will be sparse and the diverse array of data types will be large. Therefore, determining the most critical processes and parameters that control potential hydrological and transport scenarios is essential.

Internationally, research of hydrological and transport processes in the context of HLW repository performance, has been extensive. However, most of these studies have been conducted for sites that are within tectonically stable regions. Therefore, this literature review has been conducted to assess the applicability of the output from some of these studies to the geological environment in Japan. Specifically, this review consists of two main tasks:

Task 1 – Definition of Important Hydrologic and Transport Processes

Task 1, which is documented in this report, was to review the major documents of the main HLW repository programs around the world to identify the most important hydrologic and transport parameters and processes relevant in each of these programs. The review was to assess the relative importance of processes and measured parameters to site characterization by interpretation of existing sensitivity analyses and expert judgment in these documents. The processes examined by this review have focused on hydrologic parameters (e.g. transmissivity, flow path length, hydraulic gradient, advective porosity, flow wetted surface, etc.), physical transport parameters (e.g. sorption coefficients and parameters controlling diffusion rates and capacity), and chemical transport parameters (e.g. oxidation/reduction, colloids, etc.). These parameters were specifically evaluated in regards to their method of evaluation, their impact on the site selection and eventual performance assessment process, and the possible influence of active tectonics on their values.

The HLW programs reviewed in this report include the countries of Belgium, Canada, Finland, France, Germany, Great Britain, Spain, Sweden, Switzerland, and the USA.

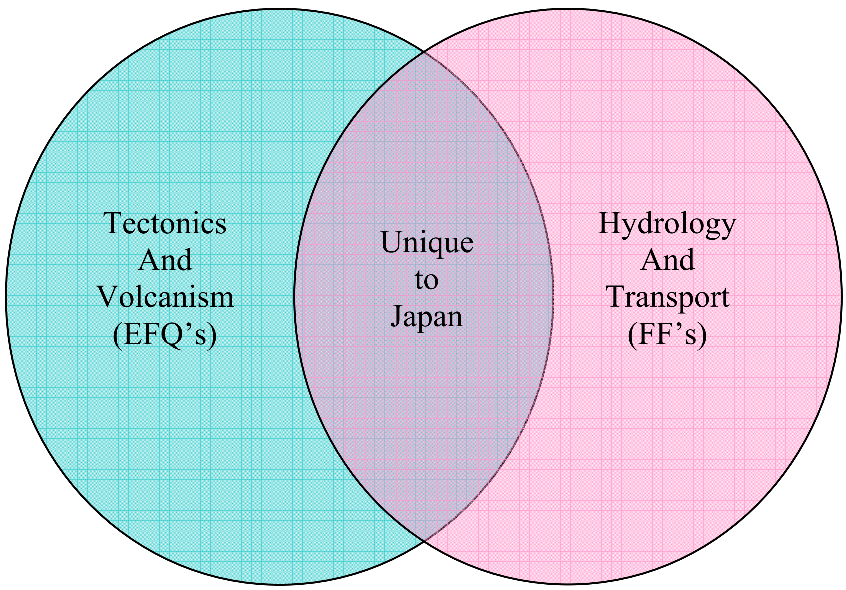

Figure 1 - The siting of a HLW repository in Japan must account for the union of active tectonics and hydrology.

Task 2 – Mini-Workshop to Prioritize Hydrologic and Transport Parameters

The results of Task 1 were presented at a mini-workshop held in Japan on March 23, 2006. The workshop was used to prioritize hydrologic and transport parameters in the context of the geology of Japan. One of the outputs of the mini-workshop was an accepted evaluation of the important parameters and processes or characteristics related to hydrology and physical/chemical transport for selection of PIA's and DIA's within the Japanese program. In addition, strategies for how to address technologies for gaining information on these parameters and where and when to focus efforts on these issues was also discussed. The outcome of this workshop is detailed below in Section 7.

This report is organized into seven main sections, the first of which is this introduction. Section 2 presents a general overview of groundwater flow and transport processes, and some of the important parameters that are used in modeling and or describing these processes. The next section presents a detail of each HLW repository program reviewed as part of Task 1. Each detail describes the geologic environment considered by each program, the available data and the methods whereby those data were analyzed, new data that may have been attained as part of the characterization process, and an assessment as to the applicability of the programs methods and analyses to the active geology of Japan. Section 4 summarizes the important lessons learned from the literature reviews that are detailed in Section 3. Section 5 examines the peer-reviewed literature that is separate from the HLW programs that address hydrology in the context of active tectonics. Section 6 discusses a prioritization and planning process called the N^2 Impact Matrix that has been successfully used in the USA, Great Britain, and Sweden. The discussion is framed as a suggested method that could be used by NUMO to identify the important processes and parameters at all stages of repository development. Section 7 presents a detailed account of the workshop that was held as part of Task 2, highlighting the important conclusions and points of the technical and discussion sessions.

1.1 Generic Description of Hydrologic Parameters

In general, the hydrogeologic characteristics of host rocks for a HLW repository should have groundwater flow systems that exhibit long-term stability and low groundwater flux. The conditions should also be chemically reducing (assessed by redox measurements, lack of dissolved oxygen), with moderate pH and temperature. Ideally the location would be hydrologically simple, meaning characterization and prediction of future states would be more accurate. Together, these characteristics determine the isolation potential of the host rock and comprise the most significant barrier to HLW's entering the biosphere.

This section presents a generic overview of the parameters commonly used in characterizing a potential site with emphasis placed on those parameters that influence the above characteristics the most. Since the intent of this study is to examine the site selection process at the regional scale, we will concentrate only on those parameters that are of importance at those scales and that would be potentially evaluated during the preliminary site investigation.

1.2 Governing Equations

The purpose of describing the geological environment is two-fold. First is the necessity to piece together the geologic history in order to more accurately predict the geologic future of the site. The second purpose is to provide a basis for which to predict the groundwater flow-field and the eventual transport and fate of radionuclides.

Before beginning a discussion of hydrogeological parameters, it is useful to review the equations that govern flow and transport through a geologic system. In its most basic form, the three-dimensional flow through a fully-saturated, confined, porous medium can be described by the following governing equation (Freeze and Cherry, 1979):

$$S_s \frac{\partial h}{\partial t} = -\frac{\partial}{\partial x_i}\left(K_{ij} \frac{\partial h}{\partial x_j} \right) + SS \qquad \textbf{(1)}$$

where h is the hydraulic head, S_s is the specific storage, K_{ij} is the hydraulic conductivity, SS is a source or sink term, t is time, and x_i is the spatial direction. The solution $h(x,y,z,t)$ describes the value of the hydraulic head at any point in a flow field at any point in time. An accurate solution requires the knowledge of the basic hydrogeological parameters, S_s, and K_{ij}. The evaluation of these parameters is difficult due to the fact that they are composite parameters consisting of more basic components that characterize both the fluid and the medium. The hydraulic conductivity is represented by:

$$K_{ij} = \frac{k_{ij}\rho g}{\mu} \tag{2}$$

where k_{ij} is the intrinsic permeability, ρ is the fluid density, g is the acceleration of gravity, and μ is the fluid dynamic viscosity. Likewise, the specific storage is described by:

$$S_s = \rho(\alpha + \beta n) \tag{3}$$

where α is the compressibility of the geologic medium, β is the compressibility of the fluid, and n is the porosity. Thus, for the purposes of predicting groundwater flow, the base parameters are those of the fluid (ρ,μ,β) and those of the geologic medium (k,α,n).

For transport of a conservative constituent in a three-dimensional porous media, the governing equation is (Freeze and Cherry, 1979):

$$\frac{\partial(nC)}{\partial t} + \frac{\partial}{\partial x_i}\left(q_i C\right) = \frac{\partial}{\partial x_i}\left(nD_{ij}\frac{\partial C}{\partial x_j}\right) + SS + R \tag{4}$$

where C is the concentration of the contaminant, D_{ij} is the hydrodynamic dispersion coefficient tensor, q_i is the Darcy velocity as calculated with (1), R is the reaction term, and all other terms are defined above. Like the hydraulic conductivity, the dispersion coefficients are further defined by (Fetter, 1999):

$$D_{ij} = \alpha_{ij} q_i n + D^* \tag{5}$$

where α_{ij} is the dispersivity, D^* is the molecular diffusion coefficient, and all other terms are described above.

Many different forms of equations (1) and (2) exist as do analogous versions of the heat equation and the like, that describe different conditions and processes (e.g. unsaturated flow, reactive contaminants, dual porosity, etc.), but the issue remains the same; *the characterization of base parameters that describe the fluid, the contaminant, and the geologic medium at all points in space and in time need to be <u>suitably</u> evaluated before an <u>accurate</u> assessment can be made*.

While the above statement might seem obvious at the outset, it is the implementation and execution that proves to be problematic over time. To begin with, data are usually sparse on both a spatial and temporal scale, especially at the PIA stage. Secondly, data may come in many forms, such as transmissivity estimates from pump tests, geophysical soundings, aerial surveys, and so on. The question becomes how to merge these different data types to provide the most accurate assessment of the site. It should also be noted that what may be suitable and accurate at the PIA stage, will most likely not be adequate at the DIA stage, meaning the data requirements will change as the site characterization process moves forward.

For the purposes of assessing the quality and performance of a potential site, equations (1) and (2) become further complicated by the fact that the base parameters are influenced in the near field, by anthropogenic activities, such as construction of the waste drifts and heat generation from the waste. With respect to far-field investigations (i.e., regional scale), active tectonics such as that found in Japan, can have the same influence on these parameters; for example, changing stress fields can impact the rock permeability, k, changes in temperature can impact the fluid viscosity, μ, sorption rates, and so on.

To apply equations (1) and (2), assumptions must be made that both the dependent and independent variables are constant within a given control volume. This implies homogeneity across some distance in the x, y, and z directions. Since geology is inherently heterogeneous in time and in space, this assumption leads to conceptualizations of a site that may be less than ideal. However, this also means that parameter estimations need only be as accurate as the spatial and temporal resolution of the model. With regards to this study, the question becomes, 'What is the long-term impact of active tectonics on the spatial and temporal distribution of these parameters and is that something that needs to be conceptualized when assessing a PIA?'.

1.3 Hydrogeologic Characterization

The purpose of a hydrogeologic characterization is to quantitatively evaluate surface and subsurface features that influence the movement of water through the geologic medium. Thus, for PIA assessment, the challenge lies in using relatively sparse data to extrapolate and capture the dominant influences on the regional groundwater flow (Gelhar, 1993). At this stage, the distribution of the hydrologic inputs and the hydraulic properties of the subsurface in both time and space will not be known in detail. The goal then, is to concentrate on the use and collection of data that describe the dominant characteristics of the regional flow system as well as the spatial and temporal variations of those characteristics.

When conducting a hydrogeologic investigation, the first step is to characterize the geology (Stone, 1999). Generally, geologic characterization is categorized as either a geologic condition or a geologic feature. Geologic conditions are the temporal forces and patterns that distinguish a site, such as the general stability or activity of the area. Geologic features on the other hand are the products of various structural and geomorphic processes. A list of geologic phenomenon that may be characterized in a hydrogeologic study is shown in Table 1 (Stone, 1999).

Important questions that should be asked when assessing these conditions and features are:

- What geologic materials underlie the study area?
- What is their thickness and extent?
- What are their lithologic characteristics?
- How uniform are these characteristics across the area?
- What is the nature of the contacts between each lithologic type?
- Is the area tectonically active?
- Is it subject to volcanism?
- Is it in an area of high heat flow?
- Is it prone to flooding?

Table 1 − Geologic phenomenon that may be characterized in hydrogeologic studies

Geologic Conditions	Geologic Features
Stratigraphic sequence	Unconformities
Tectonic stability Subsidence Uplift Seismic hazard	Structures Folds Faults; Joints
Volcanic activity	Depositional landforms Sedimentary Volcanic
Heat flow	Erosional landforms Fluvial Glacial Karst Eolian Marine
Erosional/depositional	
Prone to flooding	

The hydrogeologic characterization can only occur after a base understanding of the geology is attained. Hydrologic features that should be considered for the PIA phase are:

- Surface water features
- Topography
- Precipitation
- Head levels from existing wells
- Existing borehole logs
- Other existing data (e.g., geophysical, water chemistry, etc.)

As described in NUMO (2004), the important questions to answer with the hydrogeologic investigations are:

- Is the area hydrologically simple?
- Are groundwater fluxes generally low?
- What is the redox potential?
- Is the area hydrologically stable?
- Where are the main recharge and discharge areas?
- What are the main geologic factors that influence the hydrogeology (e.g., fractures, aquitards, etc.)?

Depending on the amount of data, the conditions at the site, and the ease of interpretation, it may not be possible to answer all of these questions.

1.4 Parameters

To facilitate a comparative regional site evaluation, characterization data as described above need to be translated into parameters that can be used to evaluate the transport and fate of radionuclides over time. At the PIA stage, this evaluation may rely only on conceptual models or possibly coarse-grid numerical models. For a regional scale assessment, specific studies for site characterization could include some or all of the following six types of studies (Karasaki et al., 2005):

- Climate and infiltration
- Geology, structure, and physical properties
- Geophysical investigations
- Hydrologic and hydrogeologic properties
- Geochemistry and isotope data
- Mechanical properties

For a PIA, the types of characterization will be largely limited to existing data, surface observations, and published reports (NUMO, 2004). Table 2 lists the primary measurement or data type by study area as well as the base parameter(s) that can be evaluated from those data. This is not intended to be an exhaustive list but rather it points out that there are numerous data and measurements that are used to evaluate a relatively small number of parameters. It is important to note, that each primary measurement is usually combined with other primary measurements (e.g. combining geophysical and geological observations) to form a better picture of the site conditions.

Table 2 − Studies used in a hydrogeologic characterization (Karasaki et al., 2005).

Study Area	Primary Data/Measurement	Base Parameters
Climate and Infiltration	Precipitation, temperature, pressure, humidity, evapotranspiration, wind velocity, wind direction	Recharge to groundwater
Geology, Structure, and Physical Properties	Stratigraphy, lithology, tectonic stability, fracture properties (frequency, density, connectivity, spacing), bulk porosity, matrix porosity, mineralogy, spatial variability, brittleness	Intrinsic permeability, application to reaction kinetics (sorption, colloid-facilitated transport parameters, etc.)
Geophysical Investigations	Aeromagnetic and gravity surveys, magnetotelluric methods, seismic reflection and tomographic seismic imaging, borehole log data (caliper, gamma ray, density, resistivity, neutron porosity)	Spatial variation of geologic units, existence of faults and unconformities: used to develop spatial variation of permeability and porosity.
Hydrologic and Hydrogeologic Properties	Effective porosity, hydraulic gradients, water table elevations, groundwater discharge, pump tests	Specific discharge, flow direction, transmissivity (permeability), specific storage
Geochemistry and Isotope Data	Isotopic field measurements, tritium signatures, speciation and solubility, chemical composition, TDS, Ion-exchange reactions, mineralogy	Recharge rates to groundwater, diffusion and sorption rates, colloid-facilitated transport parameters
Mechanical Properties	Grain density, thermal conductivity, heat capacity, thermal expansion, compressibility, brittleness, mineralogy	Transient responses to local (near-field) and regional (far-field) stresses

2 Evaluation of International HLW Programs

This section presents a detailed summary of the major HLW repository programs in existence today. This review is based on the major documents produced by each program and concentrates on the preliminary site investigation stage of each program, with the final intent to evaluate those parameters that were most important to each programs decision making process. The programs all lie on a continuum from programs that are just beginning their repository siting process to others that have selected a site and are currently undergoing very detailed investigations.

As a summary, very few programs are directly addressing the role of active tectonics on the hydrology of a site, especially at the far-field such as the scale of a PIA. However, many of the programs do give acknowledgement to the fact that some of these parameters may be sensitive to active tectonics, but then use the assumption that the probability of significant changes will be small.

Emphasis during the review was also placed on how each program interacts with the public and how they disseminate their technical information. Generally, every program (some through trial and error) have recognized that public involvement and public acceptance is a key part to the HLW repository and in one way or another, they have all gone to great lengths to include the public in the decision making process. Websites that contain links to technical and summary reports are the most common medium for distributing technical information, with some holding public workshops, maintaining 'Information Centers' at the worksites that are open to the public, and providing tours and talks by appointment to larger groups. Recognizing that the site selection process is a long-term process, several programs have placed emphasis on educating school-aged children about the concept and technical aspects of a HLW repository.

2.1 Belgium

In Belgium, the responsibility for storage and long-term management of radioactive waste is held by a public agency, the Belgian National Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS), which was created in 1980. In addition, the Belgian Nuclear Research Centre (SCK/CEN), a public, non-profit research institute is also involved in researching the geological disposal of HLW. In 1995, ONDRAF/NIRAS and SCK/CEN created the Economic Interest Group (EIG) Euridice, which has the task of demonstrating the feasibility of radioactive waste disposal in clay layers that can be found in Belgium. In 1980, the construction of an underground research laboratory (High-Activity Disposal Experimental Site - Underground Research Facility – HADES-URF) commenced in the Boom clay at Mol-Dessel. The initial purpose of this URL was to determine if it was possible to construct a repository in the plastic clays that are found at Mol-Dessel. After it was demonstrated that it was possible, other *in situ* experiments related to geological disposal have taken place.

A very important aspect of this URL, as well as the current status of geological disposal research currently being conducted by ONDRAF/NIRAS, SCK/CEN, and EIG Euridice, is that it is considered solely a research and development program, meaning that it is not intended to be part of the site selection process. The principal question being asked is whether or not a safe solution for deep geological disposal of HLW can be achieved in Belgium. Therefore, in the site selection for the formations to be studied, no formal site selection process was carried out. The selection procedure involved application of the selection criteria that was created by the

European Community (EC) in 1976 and was used for the compilation of a catalogue of geological formations that might be suitable for deep geological HLW disposal. From this process, two formations were determined to satisfy the selection criteria. These two formations are the Boom Clay and Ypresian Clay. While the Mol-Dessel site is considered a research site only, it is possible that in the future it could be considered a potential disposal site. There are no legal limitations preventing the site from becoming a HLW repository.

2.1.1 General Site Geology

2.1.1.1 Boom Clay

The Boom Clays are clays that were deposited during the Rupelian period, which spans from 36 to 30 million years ago. The Boom Clay formation is located in the Campine region, which is in the northern part of Belgium bordering the Netherlands and is east of Antwerp. The Campine encompasses an area of approximately 4000 km^2 of the Antwerp and Limburg provinces. The southern terminus of the formation is an outcrop and ranges in thickness from 30 to 50 m. The formation gently dips to the north-northeast. At the Dutch border, the formation is roughly 400 m deep and can be as much as 100 m thick. The Boom Clay is generally overlain and underlain by sand deposits. The Boom Clay is a grayish, silty clay or clayey silt that alternates in bands with a high level of pyrite and glauconite in the silt layers. The lower part and the upper part of the formation have a distinctly higher percentage of silt. The northeast portion of the formation exhibits a higher percentage of faulting than the rest of the formation, especially near the region of the Roer Valley Graben. While most of the faulting is from the Paleozoic, some of the faulting continues to be active.

2.1.1.2 Ypresian Clay

The Ypresian Clays are clays that were deposited during the Ypresian period, which occurred between 54 and 49 million years ago and is composed of several different layers. For the purposes of building a URL or repository, the most important layer is the Kortrijk Formation. These clays lay principally in the provinces of West and East Flanders, close to the Dutch border. The Kortrijk Formation gently dips northward. The southern boundary of the formation is an outcrop. The maximum depth of the formation, in the area of interest is 400–500 m. The thickness of the formation ranges from 50 m, at the southern boundary to 150 m along the northern boundary of the area of interest. At the “nuclear zone” near Doel, the top of the Kortrijk formation clay layer is at a depth of about 200 m and has a thickness of about 100 m.

2.1.2 Site Selection Criteria

As was mentioned previously, the criteria used to select areas of study were derived from the criteria developed for the EC survey instead of a formal site investigation with a component of performance assessment. When the HADES-URF project was started, in 1980, the EC procedure was congruent to the best practices of the time. While any site selection done today would be done in line with current international siting guidelines and recommendations, ONDRAF/NIRAS views this initial work to be valuable for narrowing the possibilities for a list of potential investigations areas. For this survey, the only type of formation considered by the Belgians were the argillaceous formations. These criterion are summarized as follows:

- Rock Characteristics
    - High capacity for ion absorption
    - High thermal conductivity
    - Very low hydraulic conductivity
    - Good geomechanical properties including high plasticity
- Formation Characteristics
    - Greater than 100 m thick
    - Large enough of an extent that a repository could be built
    - Homogeneity and continuity
        - little to no fracturation
        - little to no change in facies
    - Depth between 200 and 300 m
- Environment
    - Very low gradients of underground water movement
    - High absorption capacity of overlying rock
    - No strong geothermal anomaly
    - Low seismic activity
        - Less than a magnitude 7 (Richter scale)
        - Intensity less than/equal IX-MSK
- Tectonics
    - Simple, predictable structure
    - Low tectonic activity

In addition to this list of criteria, other factors were also taken into account. In the case of siting the HADES-URF, existing SCK/CEN facilities already were located in Mol-Dessel, which provided an existing infrastructure of personnel and facilities directly above the formation. The facilities were already in an existing 'Nuclear Zone', which simplified obtaining the required legal permissions and complying with the regional planning regulations. Confining the site to the 'Nuclear Zone' also limited the geographic extent of the geological surveys that were carried out. Additionally, limiting the initial investigation to one site and one formation reduced the programmatic costs. Some important geologic parameters were also available for use in the site selection at the outset of the process due to tunneling work done in the area and because of the Boom Clay outcrop. These parameters were principally geomechanical properties that gave a good indication as to what could be expected in the investigation area.

2.1.3 Boom Clay

The Boom Clay is considered to be the reference host formation for geological disposal research, demonstrating that deep geological disposal of HLW is a viable option in Belgium. The Mol-Dessel nuclear zone is considered the reference research site for demonstrating the technology needed for successful operation of a repository in Belgium.

2.1.3.1 Hydrology

The assessment of the hydrology of the site was done using data gathered prior to site selection. The data used was compiled in 1969 and was included in a published atlas of Belgium. No assessment as to the impact of tectonic activity was given.

2.1.3.2 Hydrogeology

The first geophysical and hydrogeological studies that were conducted in the Mol-Dessel study area were done in the mid-1970s in preparation for the design and construction of the HADES-URF. As part of this effort, six boreholes were drilled, at different depths, from which geomechanical properties, hydrogeologic properties, etc., were obtained. In the early 1980's, an additional 21 boreholes were drilled in which six had piezometers installed and hydraulic tests performed. All of the aforementioned work was performed after the site had been selected, was used for characterization of the site, and did not contribute to the selection process. A regional hydrogeological model was created using the data obtained from the hydrogeologic survey mentioned above for the parameter inputs. To get a better understanding of which parameters have the greatest impact on the hydrogeology of the system, changes such as erosion, climate change, etc., were incorporated into the hydrogeological model. However, changes to the hydrogeologic model due to the seismic activity, such as subsidence and uplift, were not assessed. Changes due to subsidence and uplift were thought to be too arbitrary and sensitive to the conceptual model to provide substantive understanding.

2.1.3.3 Hydrogeochemistry

The groundwater sampling and geochemical analysis program used for assessment of the investigation site was all performed after the Mol-Dessel site had been selected and was carried out using the network of boreholes drilled as part of the hydrogeological investigation. Data obtained includes major ions, trace elements, stable isotopes, and ^{14}C activity. Since the data were obtained post site-selection, it did not contribute to the site selection process.

2.1.3.4 Tectonic Activity

In the northeast portion of the Campine region exists a complex fault system, oriented NNW_SSE, that is associated with the Roer Valley Graben. The northeast portion of the Boom Clay study area is intersected by this fault system. Due to recent seismic activity in this system, it has been decided that further study is needed to better characterize this fault system so that the seismic risk in the Mol-Dessel area can be re-assessed. In addition to the recent seismic activity, during the excavation of the second shaft of HADES-URF, smooth, striated, polished surfaces were observed. The genesis of these discontinuities needs to be categorized and understood. In keeping with the overall thrust of this report, no research has been conducted or proposed that addresses the effect of seismic activity on the hydrological, hydrogeological, and hydrogeochemical aspects of the site. All proposed seismic related research has been focused on assessing and quantifying the risk.

2.1.4 Ypresian Clay

The Ypresian clay formation is considered the alternate host formation with the Doel nuclear zone regarded as the alternate reference site for methodological studies. Studies investigating the use of Ypresian clay as a potential repository site are fairly new and on a smaller scale in comparison to the Boom Clay. A lot of information used in assessing the site existed prior to commencement of the studies. One example of this information came from the Geological Survey of Belgium who had drilled several boreholes in the region. Hydrologic data had also been compiled before hand. Prior to construction of the nuclear power plant at Doel, several boreholes were drilled. While being helpful and providing insight, much of the prior information was incomplete due to the fact that it was done for different purposes and therefore the boreholes were too shallow, lacked piezometers, or were not cored. A series of five boreholes were drilled that provided data and allowed for a more complete characterization. Seismic surveys conducted in the North Sea showed evidence of significant tectonic activity. However, it is not known if the same activity is present in the Doel area. Since the Ypresian Clay is not the principal host formation, this review is short. The conclusion of the initial study was that the Ypresian Clay could serve as a host formation, though there are questions about the geomechanical strength that could lead to difficulties during construction. For more detailed information, including a listing of the initial material, hydrologic, thermal, etc., properties, refer to the SAFIR 2 report (NEA/OECD, 2003b).

2.1.5 Issues Remaining to be Answered

While site-selection is not intended to be the objective of the two URL's, several questions still remain regarding the suitability of a repository in each of the respective clay formations. Those questions are:

1. How will the presence of water-bearing sands above and below the Boom Clay affect the performance of a repository?
2. How truly homogenous is the Boom Clay throughout the entire investigation area and what is the actual extent of homogeneity?
3. How will the presence of faults in close proximity to the Mol-Dessel site effect repository performance?
4. What is the long-term stability of the Mol area? How will the Roer Valley Graben affect the long-term stability?
5. Need to develop a formal site selection process that conforms to international guidelines and recommendations.

2.1.6 Comparison to NUMO's Site Selection

2.1.6.1 General Characteristics

It is difficult to compare the site-selection process of the Belgian Radioactive Waste Management program to that with NUMO due to the fact that the Belgian program has actively declared that they have not embarked on a formal site selection process. All work done to date has been declared as pure research with the objective of determining whether or not it is viable to have a waste repository in Belgium, and in particular in the Boom Clay formation. The initial site selection was based on the European Community criteria used to compile the European Catalogue of sites that could potentially host a deep geological repository.

2.1.6.2 Interaction With the Public

There was very little interaction with, and input from, the general public when the Mol-Dessel site was selected for the HADES-URF. There continues to be little public input. This is due to confining selection of potential sites to declared 'nuclear zones' or to municipalities that volunteer (van den Berg and Damveld, 2000). A process is being developed to increase the dialogue and openness. The process is considering three key elements (IAEA, 2002):

- Defining who the stakeholders are
- Establishing the terms of the dialogue
- Defining the aims of the dialogue

2.1.6.3 Distribution of Technical and Programmatic Information

Many technical and programmatic reports and summary papers can be found online. The Safety Assessment and Feasibility Interim Report 2 (SAFIR 2) is available for download from the internet at:

http://www.nirond.be/engels/Safir2_eng.php

SAFIR 2 is a comprehensive overview of all the research activities that deal with radioactive waste management including an extensive summary of all geologic, hydrologic, hydrogeologic, and geochemical parameters that have been determined to date and are pertinent to describing the Mol-Dessel site.

In addition, other publications that ONDRAF/NIRAS have produced, that pertain to radioactive waste management are also available for download from the internet at:

http://www.nirond.be/engels/8.2_Pubs_eng.php

2.1.6.4 Literature Examined For This Review

Most of the information for this synopsis was taken from the Safety Assessment and Feasibility Interim Report 2 (Ondraf/Niras, 2001). Additional information was obtained from the International Peer Review of SAFIR 2 (NEA/OECD, 2003b) and from a review of the HADES-URF (Volckaert et al., 2004).

2.2 Canada

The history of the Canadian high-level waste program begins with a joint statement by the federal government of Canada and provincial government of Ontario, in 1978, tasking Atomic Energy Canada Ltd. (AECL) to verify that the permanent disposal of radioactive waste in a deep underground repository in intrusive igneous rock is safe, secure, and desirable. Prior to that that time, no site-selection activities had been undertaken. In fact, it is noted in the 'Seaborn report' (CEAA, 1998) that 'a subsequent joint statement in 1981 established that disposal site selection would not begin until after a full federal public hearing and approval of the concept by both governments'.

2.2.1 Status of Site Selection

The decision of whether or not to proceed with the step of site characterization for purposes of permanent waste disposal is identified in the most recent major programmatic document for the Canadian program (NWMO, 2005a) as a specific decision to be made in the future with the time-frame for this decision to extend for approximately 30 years. The recent programmatic documentation indicates that the entire range of questions regarding the balance of short-term and long-term monitoring of waste is being reconsidered. Radioactive waste in Canada consists of non-reprocessed spent fuel, though the option of reprocessing may also be reconsidered. This re-evaluation takes into account both existing and possible new surface facilities at or near reactors, long-term monitoring in a centralized surface or near-surface facility, long-term retrievability, and permanent disposal in a deep geologic repository.

Thus, the Canadian experience represents a case history in which, in the acknowledged absence of both a candidate site and a volunteer host community, an early decision was made, at both the national and provincial levels, regarding both the rock types and geologic setting to be considered for permanent disposal. This general decision appears to have been maintained through more than 25 years of programmatic and political progress and uncertainty. NWMO (2005a) states that the ultimate waste disposal in Canada might take place 'in a suitable rock formation, such as the crystalline rock of the Canadian Shield or Ordovician sedimentary rock'.

The presentation of the history of the Canadian program provides an example of possible problems that can happen during the site selection process, especially when technical progress and public acceptability are not aligned. The main focus here is on the Seaborn report (CEAA, 1998), since this report played a pivotal role in re-directing the entire Canadian program.

The Seaborn panel was constituted by the Canadian Environmental Assessment Agency (CEAA) in 1989, with the specific mandate of reviewing the Environmental Impact Statement (EIS) prepared in 1994 by AECL for permanent disposal of spent fuel in crystalline rocks of the Canadian Shield (AECL, 1994). The panel held meetings and hearings nationwide, starting in 1990 (i.e., prior to completion of the EIS). In 1998, four years after submittal of the EIS, they made several landmark findings and recommendations to the government.

It is specifically noted in the Seaborn report (CEAA, 1998, Executive Summary) that the panel's charter was unusual, in that it was asked to:

- Review a concept, rather than a specific project at a specific site
- Review a proposal for which the implementing agency was not identified

- Establish a scientific review group of distinguished independent experts to examine the safety and scientific acceptability of the proposal
- Review a broad range of policy issues
- Conduct the review in five provinces

This situation seemed to have arisen as a result of the very broad disconnect between technical work and site-selection efforts. The main conclusions of the Seaborn report (CEAA, 1998) concerning the 'Safety and Acceptability of the AECL Concept' are:

- The technical aspect of the AECL concept was shown to adequately demonstrate the safety at the conceptual stage of development, but from a social perspective, it has not
- The AECL concept does not seem to have the required public support to be adopted as Canada's approach for the storage of HLW

For the 'Criteria for Safety and Acceptability,' the key conclusions are:

- Broad public support is needed for the acceptance of any conceptual approach
- Safety must be viewed from two complimentary perspectives: technical and social, and thus in the technical sense, represents only one part of the acceptance criteria

The Seaborn report (CEAA, 1998) created significant turmoil within the Canadian waste-management program. The recent major programmatic document by the Nuclear Waste Management Organization (NWMO), which was itself formed in response to issues raised in the Seaborn report, constitutes a major redirection and re-thinking of the entire Canadian approach (NWMO, 2005a).

Significant non-technical documentation regarding both the causes for some of the conclusions reached in the Seaborn report (CEAA, 1998), the impacts of these recommendations, and programmatic responses to the committees conclusions and recommendations can be found in Brown, (2000), King (2002), McCombie (2003), Murphy and Kuhn (2002), NWMO (2005b), and Stanley and Kuhn (2003). These documents demonstrate that, in a potentially contentious area such as nuclear-waste management, it is critical that the relationship between social/political and technical/regulatory efforts be considered carefully.

However, a great deal of generic site-characterization work was carried out at AECL's Whiteshell Underground Research Laboratory (URL), sited in the Lac du Bonnet granitic batholith in SE Manitoba. This composite crystalline batholith, which is Archean in age (~2,600 mybp), bears a strong lithologic similarity to rocks being considered on a site-specific basis by the Swedish and Finnish programs. Therefore, the information available from the Whiteshell lab is briefly considered here.

2.2.2 Flow and Transport Data

The Whiteshell URL is constructed in the Lac du Bonnet batholith. The detailed geology of the batholith is described in the unpublished report of Brown et al. (1994). However, the general geologic setting of the batholith is described elsewhere (e.g., Chandler, 2003). In summary, the batholith (at the URL):

- Is one of a series of post-tectonic and post-metamorphic batholiths in the Bird River and Winnipeg River sub-provinces of the Canadian Shield. The batholith crystallized ~2,600 to ~2,700 mybp. Due to the post-tectonic setting, internal deformation should be minimal.

- Has a surface extent of ~1400 km^2, and extends to a depth of between 6 and 25 km.
- Is cut by two low-dipping thrust faults or fracture zones, with a deeper (third) fault present in some areas, but apparently not extending under the URL.
- Is divided by the two main thrust faults (at depths of ~200 and ~400 m) into distinctly different rock mass-quality and *in situ* stress regimes. These include:
    - ~5 km^2 of surface outcrop at the URL
    - Zones of highly fractured rock in the three sub-horizontal fracture zones or thrust faults
    - Moderately fractured rock (fracture frequencies of 1 to 5/m) with an interconnected fracture network, above ~200 m and locally between ~200 and ~400 m depths
    - Low-to-moderately stressed, sparsely fractured rock (fracture frequency generally much less than 1/m), locally present between ~200 and ~400 m
    - Highly stressed, sparsely fractured rock, with highly saline pore waters and effectively no interconnected fracture permeability, widespread below ~400 m. Horizontal stresses below ~400 m are extremely high, relative to the overburden

2.2.2.1 Parameters

Ophori et al. (1996) describe a revised regional groundwater flow model for the Whiteshell Research Area (WRA), which is some 1050 km^2 in extent, and contains the area of the Whiteshell URL (~5 km^2). The model was revised from that contained in AECL's EIS (AECL-10711), and includes 83 fracture zones, 76 of which are internal to the model. The fracture zones are interpreted to be either vertical, or to (generally) have a gentle dip of about 25°. The regional model, where data do not support another approach, characterizes fracture permeabilities as a multiple of the matrix permeability, both of which decrease with depth.

Hydrologic modeling at the site scale of the Whiteshell URL is described in two reports by Stevenson et al. (1996a; 1996b). Stevenson et al. (1996a) describe the conceptual model for the Lac du Bonnet batholith in some additional detail beyond that available in Ophori et al. (1996), while Stevenson et al. (1996a) is focused on the hydrologic properties of Sparsely Fractured Rock (SFR). It is noted that the Lac du Bonnet batholith is Precambrian in age, and is composed of several plutonic intrusions. The main intrusion contains pink porphyritic granite at its upper surface and local bands of xenolithic and schlieric granite. There are hornblende-biotite and foliated granites in the eastern part of the area. Similar to other HLW characterizations in fractured rock, Stevenson et al. (1996a; 1996b) identify three zones of fractured rock (fracture zones – FZ's, moderately fractured rock – MFR, and sparsely fractured rock – SFR), each with their own set of criteria and parameter estimations. However, the amount of detailed characterization information that is readily available from the Whiteshell URL is distinctly less than is available from some of the other HLW programs.

It is also worth noting that tracer testing has played a significant role in the Canadian research in the Whiteshell URL, with tests having been conducted in FZ's, MFR, and in the Excavation Damaged Zones (EDZ's) related to seal-emplacement or seal-performance tests (Ohta and Chandler, 1997).

2.2.2.2 Interpreted Importance of Individual Parameters

Stanchell et al. (1996) examines the impacts of changes in both permeability and effective porosity, relative to the values used in the EIS. This study was intended to evaluate the performance of copper overpacks or containers, which changes the surrounding geosphere to favor slower transport through the system. For example, the near-field permeability was increased by two orders of magnitude (from 1×10^{-19} m^2 in the EIS to 1×10^{-17} m^2 in this study), while effective porosities were decreased, from $\sim 10^{-3}$ in the EIS to $\sim 10^{-5}$ in this study. The same rock-structure geometry was used in both the EIS and Stanchell et al. (1996).

One major finding was that, due to the increased advection, molecular diffusion was not a significant transport mechanism in the revised geosphere model, while diffusion was the dominant transport mechanism in the EIS calculations, leading to calculated peak dose times at the surface (after transport from the emplacement depth of 500 m) in excess of 10^5 yr (Stanchell et al., 1996). In the revised model, advection is deemed the dominant process that controls the rate and direction of transport. The time of peak dose at the surface is decreased from $> 10^5$ yr to about 10^4 yr. Minimum transport times to the surface are tens of thousands of years in the EIS model and tens of years in the model of Stanchell et al. (1996). Consistent with the objectives of the report, the principal safety feature of the model changed from the ability of the surrounding rock to slow and retard the transport to that of the engineered barrier and containers (Stanchell et al., 1996).

Stanchell et al. (1996) specifically note that: 'The permeability value of 10^{-17} m^2 (applied in the Stanchell model from 300 to 1500 m depth) is similar to the permeability assumed for the rock at depths of 300 to 600 m in Finnish and Swedish assessments of nuclear waste disposal in crystalline rocks of the Fennoscandian Shield'. This conclusion is supported separately by Stanchell et al. (1996), in which the assigned permeabilities in Swedish and Finnish studies, over the depth interval of 400 to 600 m, are within an order of magnitude of the permeability values assigned by Stanchell et al. (1996). Conversely, the baseline EIS estimates of granite permeabilities over the same depth interval are 1 to 2 orders of magnitude lower than the Swedish and Finnish estimates.

2.2.2.3 Interpreted Importance of Active Tectonics on Parameters

No discussion of the impact of active tectonics on the hydrogeology at the regional scale has been found. This is consistent with the geology of the Whiteshell URL and most likely will only be addressed if a specific site selection deems it necessary.

2.2.3 New Technologies Developed During Assessment Process

A large amount of effort was put into determining the *in situ* stress fields at Whiteshell. According to Ohta and Chandler (1997), this effort included approximately 80 hydraulic-fracturing measurements and more than 350 far-field overcoring tests. However, Ohta and Chandler (1997) also note that measurements of *in situ* stress, which can be made reliably using both hydro-fracturing and overcoring techniques at relatively low stress, cannot be used in truly high-stress regimes due to disking of the overcore from stress relief. At higher stresses, a technique was being examined that involved overcoring doorstopper strain gauges in a deep sub-vertical borehole. Using this technique, they were able to successfully gather measurements to depth of 900 m.

One of the results of this effort, consistent with the Swedish experience at Simpevarp, is that major deformation structures divide the rock mass near the Whiteshell URL into three distinct stress regimes (I, II, and III). Stress regime III, which underlies a major gently dipping FZ, is characterized by extremely high sub-horizontal stresses, with the least-principal stress (again similar to Simpevarp) being sub-vertical (Martin and Kaiser, 1996).

2.2.4 Issues Remaining to be Answered

As demonstrated in the most recent programmatic documentation (NWMO, 2005a), the entire range of issues regarding the use of nuclear power and the related issues of waste generation, storage, monitoring, retrievability, and disposal remain open in Canada. Programmatically, the impact of NWMO (2005a) appears to have postponed any decision regarding site selection for a final repository for up to thirty years or more. In addition, requirements or at least the option for long-term waste retrievability are being considered.

2.2.5 Comparison to NUMO's Site Selection Process

2.2.5.1 General Characteristics

In general, the Canadian site-selection process was intentionally postponed, by governmental decision, relative to the effort to demonstrate the technical feasibility of spent-fuel disposal. In fact, the Canadian EIS for conceptual waste disposal was completed (AECL, 1994) during the middle part of a 10-year Environmental Assessment (EA) effort, culminating in the Seaborn report (CEAA, 1998).

2.2.5.2 Interaction with Public

The Canadian waste program proceeded through the stage of a full (10-volume) EIS for disposal of spent fuel without significant input from the public.

Prior to the EIS submittal (AECL, 1994), the technical basis for a HLW disposal site was carried out in the absence of both an implementing body and legislation to regulate the disposal. This somewhat parallels the Japanese experience as described in JNC (2000). However, as evidenced by the Seaborn report (CEAA, 1998) and the recent programmatic documentation (NWMO, 2005b), this approach ended up not being successful, since it led to a 10-year delay in the overall program, and to re-opening the range of questions regarding nuclear power and nuclear waste in Canada. Since that point, Canada has re-thought their approach by adding the socio-economic concerns of its citizens to the technical assessment. In contrast, the Japanese program has put great effort into including public input from the outset by soliciting local municipalities to volunteer their areas for further study. Canada on the other hand has no such structure or clearly defined direction.

2.2.5.3 Distribution of Technical and Programmatic Information

The most recent programmatic documentation that has been made available on-line (NWMO, 2006) by the Nuclear Waste Management Organization tends to avoid technical issues, but rather, concentrates on the full range of social and political issues involved in both the use of nuclear energy for power generation, and waste disposal and/or management (NWMO, 2005a; 2005b). Additional technical status reports are also readily available through the NWMO web site. Two of the more descriptive reports are McCombie (2003) and NWMO (2005b). The

McCombie (2003) report is a programmatic status report that provides an excellent update of the various international HLW programs, with heavy emphasis on publications by the International Atomic Energy Agency (IAEA). The second report (NWMO, 2005b) provides a point-by-point discussion of NWMO's planned responses to the detailed conclusions and recommendations contained in the Seaborn report of 1998 (CEAA, 1998).

There does seem to be a significant 'gap' in the Canadian documentation, extending from approximately 1996, with the finalization of most documentation describing AECL's work at Whiteshell, to approximately 2003, when the initiation of NWMO's web-based reporting began. Between approximately 1996 and the formation of the NWMO in 2002, the Canadian program was managed by Ontario Power Generation (OPG), a utility owned by the Ontario provincial government. The OPG website can be found at OPG (2006).

2.3 Finland

Posiva has completed a major baseline-conditions report (Posiva Oy, 2003a), to 'define the current surface and underground conditions at the Olkiluoto site'. This report was completed prior to the beginning of construction of the ONKALO Underground Research Laboratory (URL). The URL will, if results are favorable, become at least part of the upper level of the repository. Posiva has also completed a large site-description report (Posiva Oy, 2005) that updates the baseline report of 2003, presents an integrated site model, and incorporates data collected during 2003 and 2004. Most of the information here is taken from these two Posiva Reports (Posiva Oy, 2003a; 2005).

The Olkiluoto site area lies on an island near the SW coast of Finland, approximately 20 km WNW of the municipality of Eurajoki. Olkiluoto Island, which is separated from the mainland only by a narrow channel (100−200 m), trends WNW-ESE, and is approximately 6×3 km^2 in size. The Olkiluoto site area, which includes the area of the ONKALO URL, lies near the center of the island.

2.3.1 General Site Geology

The Olkiluoto area is underlain by high-grade Proterozoic (> 1.3 bybp) metamorphic rocks. The predominant lithology is biotite-rich migmatitic gneiss, with an average of 30−40 % vein/leucosome material. The migmatitic gneisses (totaling ~ 63 %) are informally subdivided into "veined migmatites" (43 %), "dyke migmatites" (less than 1 %), and "mica-gneiss migmatites" (21 %), on the basis of their detailed migmatitic structures. Granite pegmatites (20 %), grey (tonalitic) gneisses (8 %), homogeneous mica gneisses (7 %), and mafic gneisses (1%) have also been identified. The literature does not make it clear if the given percentages are by weight or volume.

The Olkiluoto area has a complex geologic history (Paulamäki et al., 2002). The bedrock underwent high-grade metamorphism during the Svecofinnian orogeny, approximately 1.9−1.8 mybp. The detailed interpretation indicates four distinct phases of ductile deformation, two distinct phases of high-T/low-P metamorphism, both including migmatization, and intrusion of both syn-orogenic and late-orogenic plutons. The orogeny (and ductile deformation) was followed by intrusion of post-orogenic Rapakivi granites (1.58−1.55 bybp).

The widespread presence of effects of pervasive 'retrograde metamorphism', not mentioned in the baseline report (Posiva Oy, 2003a) is called out in Posiva Oy (2005). The retrograde alteration is estimated to have occurred approximately 1.6 bybp. The pervasive effects include micaceous alteration of feldspars, chloritization of mafic minerals, and widespread low or moderate alteration of biotite. In addition, there are areas of both fracture-controlled and matrix/pervasive low-temperature hydrothermal alteration, as indicated by the presence of illite, kaolinite, and sulphides.

The present conclusion is that the temperature regime of low-temperature hydrothermal matrix alteration and fracture infilling are the same. It was not clear whether or not the general retrograde metamorphism and hydrothermal alteration should be thought of as separate episodes, although hydrothermal alteration with regards to its possible effects on rock mass mechanical properties is discussed in Posiva Oy (2005).

Later regional geologic history includes deposition of both Proterozoic (Jotnian rocks, 1.3−1.4 bymp), and at least lower Paleozoic sediments. The Jotnian rocks are not present on Olkiluoto Island, but are preserved off-shore, and are regionally preserved in fault-bounded basins. It appears that the lower Paleozoic rocks, have been regionally removed by erosion, except where locally preserved in fault-bounded structures.

In fact, the post-Jotnian history is dominated by a long period of erosion under tropical conditions, lasting from ~1.3 bybp until ~650 mybp and including formation of bauxitic paleosols, deposition of relatively thin (lower) Paleozoic sediments, and general erosion of these in response to block-faulting movements.

The most recent history (~ the last 15,000 years) has been dominated by glacial rebound in response to melting of the overlying ice burden present during continental glaciation during the Pleistocene. Again, this process appears to have taken place both regionally/smoothly and, locally, as controlled by faults.

In this area of limited outcrop (~4 %), the originally interpreted dominance of granitic or grey gneisses in the outcrops was misleading regarding the true relative abundances of the different rock types. Therefore, it should be recognized that there is some possibility for significant changes in estimated lithologic abundances, resulting from the transition from surface-based mapping activities (without boreholes) to underground characterization (including trenches and boreholes).

Similarly, investigation trenches have also shown that depressions cannot always be interpreted as fracture zones, but are sometimes lithologically controlled. This consideration should be recognized as a possibility in transitioning from surface-based to underground characterization.

2.3.2 Structural Geology

The regional geologic history indicates multiple periods of movement along fault structures. The Olkiluoto site area is located inside an elongated regional bedrock block, 11×3.5 km^2 in size, bounded on the north and south by two regional fracture zones, with estimated widths of several hundreds of meters and lengths of five to tens of kilometers. Two intersecting fracture zones of the same scale bound the block on the east. The western boundary of the block is somewhat unclear.

There are two active seismic zones in southern Finland. All activity in these zones (and elsewhere) is interpreted as resulting from reactivation of existing Precambrian structures. The nearest recorded events are more than 20 km from the site.

Fracture features in the Olkiluoto area vary broadly in scale. For example, it is noted that the Olkiluoto regional block is divided into smaller blocks by fracture zones with estimated widths of 10 to 100 m and lengths of 1 to 5 km. At the local scale, individual/discrete fractures and smaller fracture zones (FZ) characterize the rock mass.

Most of the rock mass at Olkiluoto is only slightly fractured. The average fracture frequency is 1−3 fractures/m. The number of fractures is lower in the grey and massive gneisses than in the migmatitic mica gneisses, though this difference is not used in construction of the site-scale bedrock model. Even in short sections of granitic, pegmatitic, or mafic (amphibolite-bearing) rocks, fracturing can be highly variable, ranging from sparse (< 1/m) to abundant (3−10/m).

The report (Posiva Oy, 2005) also states that most of the fractures recorded from drill cores are filled. The majority of the filled fractures are hydraulically non-conductive, due to their healed character. Open fractures are found to be scarce and are clearly concentrated close to surface (to depths of 100−200 m) in the moderately fractured rock. The fact that most of the fractures are filled can be taken to have three implications:

1. At some time, there has been significant fluid flow in the fractures, even at depth. This is consistent with the information that the range of mineralogy in the fracture fillings is relatively uniform, including montmorillonite (expanding clay mineral), even at depth.
2. The concept of fresh granite, at least in this area, should not be taken to imply that the included fractures (or fracture zones) are fresh or unaltered.
3. No clear-cut or strong correlation between the abundance of fractures and hydraulic conductivity (transmissivity) should be expected. Such a correlation would be the case if most of the fractures were open.

It must be recognized that there are inherent biases involved in surface-based characterization. Therefore, it seems reasonable to conclude that a realistic representation of the relative abundances of fracture orientations must await underground excavation and exploration.

The structural intactness of the rock mass can be divided into two classes at the Olkiluoto site, averagely-fractured, and broken rock mass, on the basis of the Finnish engineering geological classification. In this classification, a core interval is regarded as broken if: a) the fracture frequency within the interval is more than 10/m; b) it is dominated by open and/or filled fractures; and/or c) it is mesoscopically altered and weathered. Note that there appears to be some confusion in terminology, since ‘averagely-fractured’ can include fracturing as frequent as nearly 10/m.

The Conceptual Model for Evolution of Brittle Structures

Interpretation of the broken zones, usually suggests a multiphase structural and mineralogical evolution. The first/earliest ruptures are assumed to be healed and thus have no hydraulic significance, but are detected in core samples as complicated microbreccias, or abundant vein networks and small-scale faults (slickensides). Normally, this damaged zone undergoes later hydrothermal alteration, which heals and seals the pre-existing fracturing surfaces.

In turn, the healed fracture systems control the localization of later brittle events, leading to gradual development of fractured or crushed zones along the older fracture networks or systems. Typically, significant broken zones show the older healed-fracture systems to be overprinted by a younger system of open fractures, if open fractures are present at all. In filled fractures, there does not seem to be any correlation between measured hydraulic conductivity and mineralogy of the fracture infilling. This leaves the question of how hydrologically distinct broken zones are from averagely fractured rock.

The Bedrock Model

In the Finnish program, there are two separate models, a lithologic model and a structural model (Posiva Oy, 2003a). For the lithological model, only lithological units with extensive occurrence are modeled. The structural model consists of a deterministic network of ‘R-structures’, which are mainly fractured or crushed zones, but also include zones with high hydraulic conductivity but which do not show higher than average fracturing. At present, the bedrock model only contains regional and site-scale features.

R-structures are divided into four classes, listed here with increasing levels of uncertainty in both location and properties:

- Directly observed R-structures – intersected by at least one borehole, or identified directly at the surface
- Probable R-structures – deduced from data from at least two indirect methods
- Possible R-structures – deduced from data from a single indirect method
- Other features – It's not clear why this category is included

On the basis of uncertainty, the classification shown here does not automatically translate to any functional classification on the basis of either geometric extent or hydrologic significance.

Geologic structures are classified into five types that are independent of both hydrologic properties and uncertainty of occurrence, but rather are based on the intensity of fracturing and weathering. The structural types (listed in order of increased fracturing) are:

- Hydraulic feature
- Abundant fracturing
- Fracture zone
- Major fracture zone
- Crushed zone

To date, documentation of the formal distinctions among these difference types of structures has not been located.

The baseline report (Posiva Oy, 2003a) also addresses the recognized uncertainties in the bedrock model. Those uncertainties include limited data and relatively large distances between data points, interpretation of the core samples especially with regards to the continuity of fractured structures, the representation of north-south strikes and vertical dips as interpreted from inclined boreholes, the methods and means by which to convert soft-data (e.g. geophysical data) to model parameters, and the method by which to account for the propagation of uncertainties from the data collection phase to the model output. It should be mentioned that no attempt is made to quantitatively bound any of these uncertainties. Instead, the Finnish program continues to obtain additional information, in the confidence that underground experimentation in the ONKALO laboratory will provide a better understanding of reality.

Whether or not a given characterization effort can be considered adequate depends, in part, on the planned use of the collected data. The above discussions are based on terminology contained in Posiva Oy (2003a). The more recent site-description report (Posiva Oy, 2005) significantly revises the modeling terminology for the work at the Olkiluoto/ONKALO URL's. Specifically the site-description report (Posiva Oy, 2005) describes a 'Site Descriptive Model' (SDM) that is intended to aid in integration of the different modeling efforts. Within the SDM are four sub-models that interact with each other. Those models are the 'Geological Model', the 'Rock-Mechanics Model', the 'Hydrogeological Model', and the 'Hydrogeochemical Model'. The utility of defining the different sub-models is that it allows clarification of the relationships between structural and hydrologic models.

2.3.3 Status of Site Selection

The Finnish program has completed the process of site selection for their HLW (spent-fuel) repository, assuming favorable results from the ONKALO URL. The process involved several steps and scales of activity. These are summarized in Posiva Oy (2003a) and are based on a detailed summary report by McEwen and Äikäs (2000). The site selection process can be chronologically summarized as follows:

- Posiva's focused effort started in 1983, resulting in identification of 327 regional blocks that may contain suitable conditions for a HLW repository.
- In 1984, the 327 blocks were sequentially paired down to 162, and then to 61 regional blocks.
- In 1985, 134 investigation areas (each ~5−10 km^2) were identified within the 61 regional blocks. This process included field checking most of the areas.
- The 135 identified areas were evaluated by the government (as distinct from Posiva) in 1986, leading to the definition of 85 potential study areas.
- Also in 1986, discussion with the local communities began. The effort was narrowed down to five sites in 1987.
- Preliminary site-characterization of five sites was conducted from 1987−1992, with selection of three sites for detailed characterization in 1992. At the Olkiluoto site, preliminary site investigations included geologic mapping, drilling of deep (6) and shallow boreholes (36), geophysical studies (including down-hole measurements), installation of both piezometers (shallow holes) and down-hole multi-packer systems (deep holes) to measure water levels and heads, conductivity measurements in all deep boreholes, and stress measurements in one deep borehole. It should be noted that within the English translated literature, no mention was found as to whether or not a similar level of effort was made at the other four sites that were still being considered, nor has documentation of the basis for down-selection from five to three sites yet been found.
- Detailed site investigations (Phases I and II) included complementary field investigations at three sites and extended from 1993 to 2000; Phase I (1993−1996); Phase II 1997−2000.
- Posiva recommended the Olkiluoto site to the government in 2000.
- The 2000 Posiva recommendation was reviewed by the government, resulting in a 'Decision in Principle' in December of 2000.
- The government's Decision in Principle was ratified in May of 2001, completing the site-selection process. It is not clear whether or not the Eurajoki Municipality had any remaining veto authority at this stage of the process.
- The 'Site-Confirmation Stage' began in May of 2001, with the beginning of formal planning for the ONKALO URL. It should be noted that it was the municipality of Eurajoki that granted the construction permit for the ONKALO facility (May, 2003), indicating that active involvement of the local governing bodies is continuing.
- Present planning calls for submittal of a repository application no later than 2016.

2.3.4 Status of Site Characterization

In the Finnish program, there is significant overlap between processes of site-selection and site-characterization, as discussed in the previous section. This overlap has led to use of a three-fold terminology with regards to the site-selection process; 'Preliminary Site Characterization' (PSC), 'Detailed Site Characterization' (DSC), and 'Site Confirmation' (SC). In keeping inline with the objective of this report, only the PSC phase will be discussed here.

For the PSC phase, studies were carried out at five sites and included at least field studies, development of preliminary geologic models, and preliminary evaluation of hydrogeology and geochemistry. During early parts of this stage, the Olkiluoto site appears to have been somewhat unique, since significant information was already available, due to siting and construction of the two Olkiluoto nuclear power plants (1970s) and the VLJ repository for intermediate-level waste (ILW) and low-level waste (LLW) (1988-1992). Comparison of the levels of effort expended at the five sites included in the preliminary site characterization to evaluate how balanced or objective the effort was at this stage was not investigated. However, it seems to be that both surface-based and drilling activities appear to have been conducted at all sites (Posiva Oy, 2003b).

Note that preparation of baseline reports is an integral part of all three phases for the activities at Olkiluoto. These reports are intended to describe the current understanding of site-scale flow conditions, to determine the spatial and temporal variations of the groundwater table and groundwater-pressure distribution at depth in the area, and to document the present and increasing understanding of the structural characteristics of the bedrock. Pre-construction calculations of the expected structural impact of the ONKALO facility are being developed (Posiva Oy, 2003a; Posiva Oy, 2005).

2.3.5 Flow and Transport Data

The 2003 baseline report for Olkiluoto (Posiva Oy, 2003a) contains a good summary of data available to that time. This summary is taken largely from that source.

Down-hole measurements in the bedrock, made using the HTU (Hydraulic Testing Unit), a conventional dual-packer assembly, vary between 2×10^{-12} and 4×10^{-4} m/s (~1700 measurements), evaluated over test intervals of 2, 7, and 31 m. Analogous measurements were made using differential flow logging (DFL) across a test interval of 2 m and range from 3×10^{-11} to 3×10^{-5} m/s (~7000 measurements).

Extensive studies, involving replicate measurements in the same borehole using the different measurement techniques, indicate that the different methods often yield significantly different values of conductivity. In fractured zones, the double-packer injection test (HTU) often yields a higher value than either DFL or long-term pumping tests. This is apparently due to overpressures during testing, short injection times, and near-field fracture-network properties. Another cause, in some cases, is the possible short-circuit around packers into sections of the borehole above and/or below the test interval. DFL and long-term tests yield better agreement.

Given that a large majority of the fractures encountered at depth in the bedrock at Olkiluoto are filled with secondary minerals, the relationship between the amount of fracturing and measured conductivity is not simple. In fact down-hole measurements of conductivity (standardized over test intervals of 2 m [K_{2m}]), evaluated as a function of both interval identification (as either 'sparsely-fractured rock' or 'fracture zone') and depth, indicate that for all fracture zones (i.e., everything other than sparsely-fractured rock), approximately 50 % of the measurements (456) are below the detection limit (which depends on the tool used, but is assumed to be 10^{-11} m/s in this case). The other 50 % of the values appear to be log-normally distributed between ~6×10^{-11} and 5×10^{-5} m/s. For intervals identified as being sparsely fractured, approximately 83 % of the measurements are below the detection limit, and the rest are log-normally distributed, from ~5×10^{-11} to 3×10^{-5} m/s.

Although the probability of a calculated conductivity being below the detection limit is greater in sections identified as being 'sparsely fractured', the range of possible non-zero values is essentially the same for these intervals as for intervals identified as being 'fracture zones'.

The baseline report (Posiva Oy, 2003a) presents specific conclusions regarding the relationship between fracture frequency and hydraulic conductivity. These conclusions show:

- Hydraulic properties of the uppermost 100 to 150 m are distinct meaning that hydraulically conductive fractures are more frequent at these levels.
- There is a consistent decrease in hydraulic conductivity with depth, especially in the host rock at shallow depths. In 'sparsely-fractured' rock, this appears to be true to a depth of ~150 to 200 m. However, there seems to be little or no decrease in conductivities of 'fracture zone' classified rock over the same interval.
- High conductivities are found mostly in 'R-structures', especially those identified in boreholes.
- Subhorizontal fracture zones are hydraulically the most conductive and locally, there are very good hydraulic connections between boreholes along these zones, as shown by borehole pumping tests.
- Some single fractures and fracture zones have conductivities between 10^{-5} and 10^{-7} m/s, even at depths below 500 m. From about 150 to 700 m, there is a general tendency for identified fracture zones to be higher in conductivity than 'sparsely-fractured' rock. Over the same depth interval, there is a general tendency for conductivities of both fracture zone and sparsely-fractured rock to decrease with depth.
- Below a depth of ~700 m, only sparsely-fractured rock has been identified to date (i.e., no fractured zone rock have been encountered). However, measurable conductivities have been measured to a depth of ~950 m, including values as high as ~7×10^{-6} m/s.

While the median and mean conductivity appears to decrease with increasing depth for both fracture zone and sparsely-fractured rock, the overall ranges of values within each depth interval remains relatively constant, at least to depths of ~500 m.

Within the development of the numerical models, transmissivity has been generalized to be a function of depth (Posiva Oy, 2003a). For the site-scale flow and transport modeling, there are additional generalizations that include geologic simplifications, removal of single borehole features, and the inclusion of 'expert judgment' to expand fracture features.

2.3.6 Data Collection Methods

Both standard and development data-collection methods have been widely used at Olkiluoto. The standard method for down-hole hydraulic measurements has been the Hydraulic Testing

Unit (HTU), which is a standard dual-packer assembly, but adjustable, with test intervals of 2, 7, and 31 m. Some multi-hole pumping tests have also been carried out. However, the literature identified to date describing these tests is in Finnish.

Considerable effort has been put into both surface-based and cross-hole geophysical methods, in the interest of identifying both large-scale and small-scale 'fractures zones' and/or individual fractures. However, the results have been less than completely satisfying. The main reason for this, especially in the case of surface-based studies, is the lithologic complexity at the site. Because of this complexity, deep reflectors due to lithologic contacts cannot reliably be distinguished from those due to crush zones.

2.3.7 Data Evaluation

There is extensive consideration of the compilation of the available hydraulic data into a site-scale model (Posiva Oy, 2005). The issue is not of interpreting individual test data, but rather that of how the numerous test data should be translated into a conceptual model. For the 'country rock', the SDM combines generalization of depth-dependent rock mass conductivities in five depth zones (0–50, 50–100, 100–200, 200–400, and 400−900 m) with discrete mapping of hydraulic features. Note that, without exception, the more recent conductivity ranges estimated for the different depth intervals are higher than those stated in (Posiva Oy, 2003a).

The treatment of transmissivities of discrete structures is revised in the site-characterization report (Posiva Oy, 2005). While transmissivities of most identified structures are taken directly from field measurements, two additional constraints are also applied. First, the transmissivity is constrained to be greater than that of the nearby matrix or rock mass. Second, for larger structures, the transmissivity is also assumed to be depth-dependent.

The present division of hydrochemical parameters at the Olkiluoto site includes the definition of four major zones and three sub-zones. For example, the background Cl^- concentrations range from < 10 mg/l at the surface, to ~45000 mg/l at depths greater than 600 m (Posiva Oy, 2005). The most recent compilation of both groundwater compositions and expected groundwater flow and evolution at the Olkiluoto site is contained in Pitkänen et al. (2004).

2.3.8 Interpreted Importance of Individual Parameters

To date, quantitative information on the relative importance of individual parameters to preliminary site-selection at Olkiluoto is not available. This is consistent with the fact that present planning calls for a Preliminary Safety Analysis Report (PSAR) to be completed by the middle part of 2011, after completion of the experimental phase at ONKALO in 2010 (Vieno and Ikonen, 2005).

This does not mean that Posiva is not concerned about the precision and accuracy of the data collected and the results of modeling studies at Olkiluoto. In fact, a relatively large portion of the site-description report (Posiva Oy, 2005) consists of an overall consistency and confidence assessment that is based on a Swedish protocol for the evaluation of confidence in site-characterization data (SKB, 2004a). In addition, there are several detailed qualitative discussions in the main body of the site-description report (Posiva Oy, 2005) concerning conceptual, data, and interpretative/modeling uncertainties.

The protocol for the evaluation of data and modeling confidence is extensive, and extends to consideration of both conceptual and numerical uncertainties. However, the Finnish planning does not appear to combine parallel, iterative, or interim Performance Assessments (PAs) with ongoing experimental activity focused on decreasing the uncertainties in the model parameters judged to be the most important.

A data-dominant approach as adopted by the Finnish program tends to rely on the implicit belief that additional data will make the necessary decisions obvious. In contrast, a completely model-dominant approach runs the risk of making decisions on the basis of models that are based on inadequate data. Thus, the Finnish approach appears to be fundamentally different than the Japanese approach, at least as the latter is represented in the H12 series of reports.

2.3.9 Interpreted Importance of Active Tectonics

Vertical uplift/subsidence due to glacial activity is considerable and believed to lead to reactivation of crush zones. The process occurs as a combination of two rates, a slow, regional process that involves recovery from some 650 m of maximum depression (in northern Sweden) approximately 15,000 years ago, and a fast, local process that is unloading in response to the end of more localized glaciations in the Younger Dryas (ending ~10000 BP). Local estimates indicate between 58 and 70 m of uplift over the last 7000−7500 years at Olkiluoto Island. Extrapolations indicate uplift of ~40 m over the next 10,000 years, with the general rate decreasing from the present estimate of ~6 mm/yr (Posiva Oy, 2003a).

Although not directly related to plate tectonics as is the case in Japan, active tectonics are a legitimate issue at Olkiluoto. It is assumed however, that these movements will have no effect on local flow and transport parameters because the regional responses will not be large enough to impact local conditions and the localized responses along crush-zones are well removed from the Olkiluoto site.

2.3.10 Remaining Uncertainties

Both the baseline report (Posiva Oy, 2003a) and the site-description report (Posiva Oy, 2005) discuss the remaining needs in the general area of flow and transport. In the baseline report (Posiva Oy, 2003a) it is noted that:

- There is a need for a better understanding of interactions between geochemical and hydrogeological processes.
- There is a need for special studies on how exposure of rock (during the construction and operational phases of both ONKALO and the repository) may result in the rock mass losing its reducing capability. Calculations are required that consider the primary porosity and not the whole rock or total porosity in redox buffering capacity. The logic appears to be that connected porosity, due to its connection with the local environment, will be oxidized during the construction/operational phase, while primary porosity, access to which is by diffusion only, will remain reducing during these stages.

The site-description report (Posiva Oy, 2005) contains a more extensive discussion that is based on a governmental review of Posiva’s 2003 documentation. Each major section of the report includes detailed discussion of identified uncertainties and sensitivities. The major uncertainties include:

For the Geological Model:

- Spatial distribution of rock types (both 2D and 3D)
- Heterogeneity within each generalized rock type defined for modeling purposes
- 3D distribution of alteration zones
- Heterogeneity of matrix alteration and its impact on mechanical properties
- Spatial distribution and amounts of fracture minerals

For the Structural Model:

- Existence of deformation zones
- Continuity of deformation zones
- Characteristics and properties of deformation zones, including those that are well established

For the Discrete Fracture Network (DFN):

- Identification (orientations) of fracture sets
- Fracture-size distributions
- Fracture intensity (spacing) and its coupling with surface and subsurface rock types as well as its variability with depth
- Characteristics of fracture intersections and intersections of fractures with deformation zones

For the Hydrogeological Model:

- Flow-model geometry, especially the connectivity of the fracture-zone network
- Flow-model hydraulic properties – especially the transmissivities of fracture zones
- Hydraulic conductivity of the general rock mass (sparsely-fractured)
- Flow and matrix porosities
- Flow-model boundary conditions and time dependence (for both present day and past evolution)
- Salinity distribution in the initial state
- Numerical uncertainties

For the Hydrogeochemical Model:

- Heterogeneity and data adequacy above 500 m depth
- Heterogeneity and data adequacy at depths below 500 m and near the shoreline
- Hydrogeochemistry in very-low-permeability rock
- Origin of basement brine and the impact of its dilution to subglacial groundwater and glacial water
- Hydrochemical conditions in the upper 200 m after the last deglaciation
- Development of better illustrations of 3D hydrogeochemistry
- Surficial mineral processes and long-term alteration of silicates
- Genesis of hydrocarbons (at depth); mixing of CH_4^- and SO_4^- rich groundwaters
- Microbes

2.3.11 New Technologies

2.3.11.1 System for Down-hole Measurement of Differential Flow

This tool, generally referred to as the difference flow meter, has been developed for detailed evaluation of differential flow in boreholes in fractured rock systems, due to flow into or out of fractures (Pöllänen and Rouhiainen, 2002; Rouhiainen, 1997; 2000). The normal test interval with this instrument is 0.5 m. Techniques have been developed to test with overlapping test intervals, at tool-position increments as small as 0.1 m. The theoretical flow sensitivity of the instrument over the full 0.5 m test interval is 0.1 ml/min. In the detailed (overlapping) mode, fracture-specific flows can be backed-out from a series of measurements. However, the reported theoretical accuracy in this mode is 0.5 ml/min.

2.3.11.2 System for Down-hole Sampling at Pressure

In order to investigate both dissolved gases and microbes under realistic conditions, a down-hole system (PAVE) was developed specifically to allow fluid sampling at ambient fluid pressures (Hinkkanen et al., 1996; Ruotsalainen et al., 1996). The PAVE system allows collection of high-quality samples from individual fractures or fracture zones.

2.3.11.3 New System for Measurement of Cross-Borehole Flow

It is reported in the site-description report (Posiva Oy, 2005) that Posiva has developed and tested a new tool (TRANS-tool) for measuring transverse flow through boreholes. Some modifications are presently being made to the tool, and formal documentation regarding the tool's capabilities/limitations is not yet available. A previous transverse-flow tool developed by Posiva is described in Rouhiainen (1997).

2.3.12 Data Management

All field-investigation data from the site-characterization effort have been archived using the TUTKA data-management system. This system is based on Microsoft Access, and has been in use (with updates) since 1992 (Lallo and Hellä, 1997).

It is not clear that the TUTKA system is developmental. However, the public commitment to use such a system to store all of the data collected on-site (as well as related meta-data) appears to indicate a commitment to continued technical openness. To date, it has not been possible to identify any procedures for public access to the data-management system.

2.3.13 Issues Remaining to be Answered

In the baseline report (Posiva Oy, 2003a), considerations of uncertainties are carefully divided into four factors, leading to an overall qualitative evaluation of confidence. The four factors specifically considered include:

- Conceptual uncertainty. Are the geometries, processes, and interactions among processes adequately understood
- Data uncertainty. Includes uncertainties involved in measurement and interpretation of data, as well as those resulting from extrapolation in space and time
- Spatial variability

- Scale. This variable concerns the spatial resolution of the site description (and presumably parameter measurement)

Posiva's 2003 reports, developed in support of the recommendation of the Olkiluoto site and documentation of baseline conditions were reviewed by Finland's Radiation and Nuclear Safety Authority (STUK). As summarized by Posiva in the site-description report (Posiva Oy, 2005), the STUK comments, recommendations, and/or requirements address the need for an increased level of synthesis and between disciplines, a consideration for alternative models, characterization of fracture zones and their heterogeneity, and describing the surface hydrology. The STUK comments specifically note that in order to support future predictions, there needs to be a better quantitative understanding of paleohydrogeology as well as a better integration of hydrogeology and hydrogeochemistry. They also mention the need for predictive assessment of the disturbance caused by construction of the ONKALO, as well as iterative updating and evaluation as excavation proceeds. The STUK comments appear to have lead to changes in Posiva's activities, including:

- Formation of the Olkiluoto Modeling Task Force (OMTF), which has the special role of ensuring integration between the different (field and modeling) disciplines
- Initiation of directed efforts to identify the main couplings between disciplines, and to ensure that the different disciplines handle data and reporting consistently
- Initiation of an effort to endure that the different disciplines handle uncertainty assessment consistently
- Planning for integrated assessment of the impacts of ONKALO construction
- Planning for carrying out a confidence assessment of the assembled SDM

2.3.14 Comparison with NUMO's Site Selection Process

Regarding site selection and characterization, the Finnish HLW program is demonstrably further along than the Japanese program, since local approval has already been gained in Finland for both URL construction and site-specific research, which is to be used directly in the planned Finnish repository. Therefore, the comparison of the two programs can only be a comparison of planned activities (Japan) versus experience (Finland).

2.3.14.1 Interaction with Public

Both the Finnish and Japanese programs call for extensive interactions with the local community most impacted by a potential nuclear-waste repository. From the perspective of experience, the impact on the site-selection process of the two nuclear power plants and a repository for ILW and LLW on Olkiluoto Island is not clear. On the one hand, site characterization and construction of these facilities certainly made considerable geotechnical information available for the area, even at the stage of preliminary site characterization for a HLW repository. Interactions resulting from the presence of these earlier facilities also will have established a baseline for interactions among the utility, national government, and local government. It is not yet clear if these interactions were formally considered in the Finnish process of site selection, or whether they helped the process, made it more difficult, or were effectively without impact.

It should be noted, that it was the municipality of Eurajoki that granted the construction license for the ONKALO URL (May, 2003). At this time, documentation has not been found outlining any planned ongoing role of the local authorities in the repository at Olkiluoto.

2.3.14.2 Distribution of Technical and Programmatic Information

Information on both technical and programmatic status of the Finnish HLW program is available at the web site for Posiva Oy (Posiva Oy, 2006). The site includes numerous links to both frequently updated lists of publications and information on the ONKALO URL. The Posiva web site also includes a link to Finland's Radiation and Nuclear Safety Authority (STUK, 2006), however the site appears to be in Finnish with no link to an English version.

In general, the Posiva website does an excellent job of transmitting formal technical information to the public both in Finnish and English. However, this does not hold true of for older reports or some working documents.

2.4 France

The National Agency for Radioactive Waste Management (ANDRA) was given the responsibility of accessing the feasibility of deep geological disposal of high-level, long-lived, radioactive waste as the result of the passage of the 'Law of 30 December 1991'. Under this law, two geologic environments, clay and granite, were to be considered (ANDRA, 2005b). Out of this authorization, the Meuse Haute-Marne site was selected for the construction of an underground research laboratory (URL) in an argillaceous (clay) rock. The following is a brief time-line ranging from initial authorization of the research program through the construction of the Bure URL (ANDRA, 2005a):

- **1994-1996**: *Preliminary repository design work*, including list of data and performance parameters necessary for site selection.
- **1997**: *Geological survey of two sites*, Meuse Haute-Marne and Gard. At the Meuse Haute-Marne, three boreholes were drilled and a 2D geophysical survey was conducted with a corresponding geological mapping.
- **1998**: *Initial repository design* work taking into account site specific information.
- **December 1998:** Meuse Haute-Marne site selected as site of the first URL.
- **1999-2001**: *In-depth study of site geology* using 3D geophysical survey. Access and auxiliary shaft construction begins.
- **2003-2004**: Additional deep and sometimes deviated boreholes drilled around the URL site.
- **October 2004**: Auxiliary shaft reaches total depth of 490 m.
- **November 2004**: Experimental drift attached to main shaft available at 445-meter depth.
- **2005**: Excavation and operation of experimental drifts at bottom of auxiliary shaft.

While significant progress has been made in the construction of the URL in clay, as a result of significant public pressure, the selection process for a URL in granite has been suspended since 2000. Since this time, ANDRA's research efforts in granitic rock has been based on work done at foreign URL's such as Grimsel, in Switzerland, and Äspö, in Sweden (NEA, 2005).

2.4.1 General Site Geology

The study area lies in a region defined as the Parisian basin. The basin can be described as a bowl that has been filled with a succession of horizontally oriented sedimentary layers that exhibit little variation in thickness or composition within the layers. The layers are composed of limestones, marls, and clay formations. This region can be described as containing a very simple, predictable geological structure.

At the site chosen for the clay URL, the surface layer is the Barrois limestone, which runs to a depth of 25 m. The next layer is the impermeable Kimmeridgien marl, which extends to a depth of 125 m. This is underlain by the 300-m-thick Oxfordian lime, which extends to a depth of 425 m. The host layer, Callovo-Oxfordian argillites is next and extends from 425 m in depth to about 550 m in depth for an average thickness of 130 m. This layer dips about 1° to the north-west. The bounding layer beneath the host layer is a Dogger limestone with a thickness of 250 m. Both the Dogger and Oxfordian limestones exhibit low permeability (ANDRA, 2001b).

The study area is located in a region that has a very low deformation rate and very low potential for seismicity. It is hypothesized that the tectonic stresses are absorbed at the boundaries of the domain, which are the lower Rhine graben, the Ardennes structures, the Alsace graben, and the northern portion of the Massif Central (ANDRA, 2001a).

2.4.2 Site Selection Criteria

The site selection process was principally influenced by the long-term safety functions of the repository. The highest function of deep geological disposal is that it must protect waste against erosion and major human activities. On a repository time-scale of hundreds of thousands of years, this should be superficial and in the case of erosion should not affect greater than 100 m of cover. In preventing radionuclides from coming in contact with the biosphere, the repository must fulfill three major functions, all of which rely heavily on the geologic and hydro-geologic environment of the site and the geochemical properties of the host rock. These functions are (ANDRA, 2005a):

- Prevent water circulation
- Limit radionuclide release and immobilize radionuclides inside the repository
- Delay and reduce the migration of any radionuclide released by the waste

In context with these limiting functions, the nature of the site selection parameters was essentially set. The characteristics state that the formation must have (ANDRA, 2005a):

- low permeability
- low porosity
- low hydraulic gradients
- favorable physical and chemical environmental conditions that will minimize impact on the waste containers
- favorable geochemical conditions that limit the mobility of the radionuclides
- high radionuclide retention capacity
- low diffusion coefficient

In addition to parameters that are principally concerned with radionuclide transport other factors include (ANDRA, 2005a):

- sufficient geotechnical strength for allowing drift excavation and construction of underground structures without causing significant fracturing and fissuring in the local material, which can introduce an increase in permeability
- chemically stable enough to buffer the effects of externalities, such as increased oxidation or increases of alkalinity resulting from the degradation of concrete, introduced through the construction process
- sufficient thickness of the host layer to provide significant buffer zones above and below the repository
- relative homogeneity of material, which provides for predictability as well as evidence of geologic stability
- area of low seismicity
- sufficient depth of overlying material that can protect from climatic changes
- lack of economically valuable geologic resources

In surveying the Meuse/Haute-Marne site, the preliminary investigation had the good fortune of having access to a fairly extensive collection of previously obtained geologic and hydrogeologic records, including surface geologic mapping, hydrogeologic data of boreholes and springs, and geophysical seismic surveys. This information was collected by various entities in the process of oil exploration. Additionally, two deep, cored boreholes were drilled in the site region, 15 km apart. These boreholes were continuously logged, using conventional oil industry techniques, and used to obtain material parameters (electrical resistivity, sonic velocity, porosity, density, etc.) and core samples, which were used to conduct laboratory tests and analyses and to make hydrogeological measurements (ANDRA, 2005a). These measurements preliminarily confirmed that the Callovo-Oxfordian clay layer had sufficient rock strength for construction of a repository, that the rock had low permeability, and that it was probably of sufficient depth to accommodate a repository. In addition, it demonstrated that the hydraulic gradients were favorable for locating a repository in the formation. It also provided preliminary geomechanical, geochemical, thermal, and hydrogeological property values of the rock. In short, it showed that it may be feasible/favorable to construct an URL at the Meuse/Haute-Marne site (ANDRA, 2005a; NEA/OECD, 2003a).

Since the beginning of the site selection process, a total of 27 boreholes, each several hundred meters deep, have been drilled. A 2D and a 3D seismic campaign have been conducted on the site as well as an extensive geological survey. Both the main access shaft as well as an auxiliary shaft have been sunk to a depth of 490 m and 445 m, respectively, with related experimental drifts at the terminating depths. As a result of these various activities, the site has become very well characterized and the geological environment has become well understood. The following is a list of items that demonstrate the site knowledge gained (ANDRA, 2005a).

1. The geologic profile is a simple, regular, layered geometry and essentially flat. Any tectonic deformation that has affected the region has been slight and limited to the boundaries of the study area.
2. The site is located in a geologically stable environment. The Meuse/Haute-Marne site is located on what is called the 'west European' plate and is located nearly 350 km from the tectonically active regions of the plate, which are located along the main faults surrounding the plate. For the past 65 million years, the site has been marginally affected by tectonics. In fact, it is an unusually non-seismic region.
3. The site is located in a region lacking in exploitable natural geological resources such as coal or hydrocarbons. Several times during the 20th century, exploration for natural resources such as coal and oil was undertaken with negative outcomes for finding exploitable reserves.
4. The Callovo-Oxfordian argillites form a uniform, relatively homogenous layer approximately 130-m-thick, at an average depth of about 490 m, over a surface area of more than 350 km^2. The argillites are laterally uniform throughout the study area. Vertically, there are three sequences of mineral composition, containing varying amounts of carbonates, clays, and quartz and feldspars. The median sequence has the highest percentage of clays and is centered, vertically, in the formation. In addition, it has been designated as the best candidate for a possible repository.

5. No faults or cracks, which would affect the continuity of the Callovo-Oxfordian, have been discovered during the geological mapping, during the seismic reflection campaigns, or intersecting the boreholes. All faults that have been located were outside of the study area.
6. The Callovo-Oxfordian geological formation yielded very low permeabilities, with measurements ranging between 10^{-13} to 10^{-14} m/s. This low permeability can be explained by the clay's affinity for water and by the very fine pore size, on the order of 0.05 µm. The permeability values measured demonstrated uniformity regardless of scale size, ranging from sample size scale to repository scale. Additionally, due to the relatively high quantities of smectites in the Callovo-Oxfordian formation, the formation has the ability to retain a large quantity of radionuclides.
7. Geomechanically, the argillites showed strength sufficient to allow for conventional means of shaft and drift construction.
8. The formations surrounding the Callovo-Oxfordian formation, the Oxfordian and Dogger limestones (overlying and underlying, respectively) both have low permeabilities, ranging from 10^{-10} to 10^{-8} m/s, for the Dogger, and 10^{-9} to 10^{-7} m/s, for the Oxfordian. Additionally, the hydraulic heads measured in the Oxfordian and Dogger formations are similar and therefore do not represent a driving force of the water displacement in the Callovo-Oxfordian formation.

Due to the low probability of a seismic event over the repository time scale of 10^5-10^6 years, at the Bure URL, all repository structures are to be designed to withstand a hypothetical magnitude 6.1±0.4 earthquake (ANDRA, 2005a). Based on this design criterion, it can be seen that seismicity is thought of as having little consequence to the operation of a repository. Subsequently, within the French HLW repository program, there has been little research into tectonics and how it might affect the hydrology associated with the siting, construction, and operation of a deep geologic HLW repository.

2.4.3 Issues Remaining to be Answered

Since the general public rejected the siting of a granitic URL in France, how ANDRA will be able to comply with the requirement to site and construct a granitic URL remains the main issue to be answered. Now that construction on the experimental drifts in the argillite URL has been nearly completed, the other broad issue remaining is simply the completion of planned experiments and the associated data gathering process.

2.4.4 Comparison to NUMO's Site Selection Process

2.4.4.1 General Characteristics

No formal siting criteria has of yet been established, at least no process that would directly correlate to the three phase NUMO process of selecting preliminary investigation areas, followed by selecting detailed investigation areas, followed by selecting a repository site (NUMO, 2004). In June 1991, a basic safety rule was issued that specified the performance goals that needed to be met to ensure safe operation of a repository. From this document, in concert with completed research conducted in the URL, the basis for the site selection criteria will be established.

2.4.4.2 Interaction with the Public

By law, elected representatives and the general public must be informed of the steps that are taken by ANDRA while establishing the URL as well as the research activities being performed at the URL following its construction (IAEA, 2002). Public protest led to the suspension of site selection for a URL in granitic rock, demonstrating that the general public does have influence in the overall process.

2.4.4.3 Distribution of Technical and Programmatic Information

ANDRA maintains a website from which reports can be downloaded. The website is:

http://www.andra.fr/interne.php3?publi=publication&id_rubrique=134

2.5 Germany

English translated literature was difficult to obtain and time constraints did not allow for translation. However, several documents were found that has allowed for a comprehensive assessment of the German repository program. The introductory and historical remarks in this section are synthesized from independent programmatic reviews (van den Berg and Damveld, 2000; Lidskog and Andersson, 2001). Details of AkEnd's proposed procedure were taken from the publicly-available Final Report (AkEnd, 2002) and a more general brochure released in December 2002.

2.5.1 Background and History

Historically, the German government has considered deep geological disposal the only alternative for long-term radioactive waste management. Spent fuel is currently either stored on-site at the power generation station or at centralized interim facilities (at Gorleben and Lubmin, respectively). Prior to June 2005, contracts for reprocessing were in place with plants in the UK and France. All HLW associated with reprocessing is currently housed at Gorleben. Previous attempts at site selection for HLW disposal focused on the salt dome at Gorleben but the coalition government (in 1998) drastically altered the political landscape, resulting in a moratorium on all Gorleben characterization efforts as of October 2000. The political agenda of the coalition government (1998-2000) further established guidelines for waste management and disposal, specifically calling for:

- the development of a new waste management plan
- a single repository to be constructed in a deep geological formation that will be utilized for all waste and that must be operational by 2030

In 1999, the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU) established the Committee on a Selection Procedure for Repository Sites (AkEnd). AkEnd's mandate was to develop the procedure and relevant criteria for identification and selection of the future disposal site. The task of implementation will reside elsewhere, to be decided during Phase II of their recommendation as discussed below. Within the legal framework of the licensing for the construction and operational components of a new repository, compliance guidelines stipulate several constraints on the site selection and final characterization efforts as follows:

- Exposure risks to workers and the public in the repository area from (i) direct and scattered radiation; and (ii) radiation from waste products mobilized in gaseous or fluid effluents must be considered under normal and accident conditions
- Characterization of the host rock response to the heat generated during radionuclide decay
- Criticality safety must be demonstrated during operation and post-closure periods
- Long-term radiological risks to repository surroundings due to radionuclide migration through groundwater systems must meet legal dose standards

Preliminary review from AkEnd indicated that they would design a selection process and criteria that recognized the importance of the integrated geological system, rather than simply the host rock itself, that provides the long-term isolation required. Their formal recommendations were forwarded to the public and government in December 2002. Reviews of the AkEnd procedural recommendations, and of the preliminary geoscientific components of the first two steps proposed in the site selection process, are presented in the following two sections.

2.5.2 Site Selection Criteria

AkEnd defined additional requirements beyond the political framework to be considered during their deliberations. These are related to the four legal guidelines defined above and established procedures for:

- public participation
- protection and safety principles (then) in place will be included as constraints
- current and projected best-estimates of all radioactive waste will be used to designate repository capacity
- procedure will be consistent with 2030 guideline on repository operability
- geologic barriers will be emphasized in the multi-barrier definitions for repository concept specifications
- isolation period is on the order of one million years
- retrievability will not be included in the design concept, nor planned for in the analysis in the procedural assessment
- assessment criteria and weighting functions, and consequences at each sequential step of the process, are to be specified *prior* to each respective step
- data uncertainties must be properly propagated through the decision process

The site selection procedure is structured as a three-phase process with two additional phases that comprise the licensing and construction phases. These are shown in Table 3.

Table 3 − Site selection and development phases for Germany.

Phase	Proposed Period	Description
I	1999-2002	Development of a selection procedure, including formal recommendations
II	2003-2004	Political/legal agreement on the selection procedure (*Note: At present, this Phase is still incomplete*)
III	2005-2010+	Implementation of the selection procedure, with recommendations that two sites should be pursued through underground characterization
Licensing	2010+-open	Development and presentation of safety case to the licensing authority (5-year minimum; must allow time for construction)
Construction	complete by 2030	Construction of surface and subsurface facilities (up to 5 years duration)

2.5.3 Regional to Site Delineation

Phase III recommendations (i) detail how the site selection process will proceed, (ii) define the central criteria (both geoscientific and socio-economic) that will be used in each step, and (iii) describe how citizen participation will be integrated. AkEnd suggests that a period of up to 10 years will be needed to fully characterize the final two sites to be subjected to underground exploration. The selection procedure is divided into five components (Table 4), resulting in a repository site that would (ideally, from the 2002 perspective) begin the required legal licensing evaluations by 2010.

Only geoscientific criteria (exclusion; minimum requirements; favorability factors) are utilized in the first two steps. This emphasis highlights the long-term safety characteristics that dominate the selection weighting. These steps constitute the region-to-site selection process common to most recent publicly-oriented processes. At the beginning of Step 3, the field of possible sites will have been narrowed to 3-5 alternatives, ranked in geoscientific/safety favorability order according to the criteria, and weight functions, for the determination of particularly favorable partial areas as implemented in Step 2. Details of the geoscientific criteria categories are discussed below.

2.5.3.1 Exclusion Criteria (Step 1)

Five exclusion criteria are stipulated in Step 1 as:

- Large-area vertical movement (uplift rate) must be < 1 mm/yr over the predictable period
- No active fault zones in repository area
- Seismic activity must not be higher than Earthquake Zone 1
- No observed volcanism during the quaternary, nor any expectation of such in the future
- Groundwaters in the isolating rock zone must not contain measurable tritium or C^{14}

These criteria relate to hazards, such as (i) denudation of the repository and reduction of the geological barrier thickness; (ii) gas/fluid flow into and out of the repository by changing groundwater conditions; or (iii) creation of fast flow paths associated with newly-strained faults or joints, that with high probability would result in severe compromise of the repository system within the period of interest.

Table 4 − Proposed five-step process for site selection in Germany.

<table>
<tr><th>Procedure Steps</th><th>Proceeding, Criteria, Assessments</th><th>Instruments of Citizens Participation</th></tr>
<tr><td>1st Step
Objective: Identification of areas fulfilling specific minimum requirements</td><td>For Step 1
• Geoscientific exclusion criteria and minimum requirements</td><td>For All Steps
• Participation by Information and Control
• Establishment of an information platform
• Control committee verifies adherence to the rules of the procedure</td></tr>
<tr><td>2nd Step
Objective: Selection of partial areas of particularly favorable geological conditions</td><td>For Step 2
• Geoscientific weighting</td><td rowspan="4">Within Step 3
• Citizens forum as a central element of participation
• Center of competent experts supports citizens forum
• Round table stakeholder discussion group
• Determination of willingness to participate in Steps 3 & 4 by vote
• Preparation of regional development concepts
• Local council(s) make(s) final decision
• Orienting vote of the public and local councils at the end of Step 5</td></tr>
<tr><td>3rd Step
Objective: Identification and selection of site regions for exploration from the surface

Step backwards if necessary</td><td>For Step 3
• Planning of scientific exclusion criteria
• Socio-economic potential analysis
• Planning of scientific weighting criteria
• Specification of programs for exploration from the surface and corresponding assessment criteria
• Willingness to participate regarding exploration from the surface
• Geoscientific and mining aspects</td></tr>
<tr><td>4th Step
Objective: Determination of sites for underground exploration

Step backwards if necessary</td><td>For Step 4
• Exploration from the surface and assessment
• Orienting safety assessment
• Willingness to participate regarding underground exploration programs
• Development of test criteria</td></tr>
<tr><td>5th Step
Objective: Decision on a site

Step backwards if necessary</td><td>For Step 5
• Underground exploration and its assessment
• Safety case
• Comparison of the different sites explored</td></tr>
</table>

2.5.3.2 Minimum Requirements (Step 1)

Seven conditions are defined as minimum requirements during Step 1, relating to the hydrogeology, geomechanical stability, and geometry of the subsurface host rock zone. In certain cases, the assessment of these factors can only be predicted through modeling or by using additional data and assumptions that themselves must meet the quality assurance requirements of future safety inquiries. The seven minimum requirements are:

1. The isolating rock zone must be comprised of rock to which a field hydraulic conductivity of $< 10^{-10}$ m/s can be assigned
2. The isolating rock zone thickness must be > 100 m
3. The top of the isolating rock zone must be > 300 m
4. The repository must be constructed above 1500 m deep
5. The isolating rock zone must include an area of 3 km^2 in salt or 10 km^2 in clay/granite
6. The isolating rock zone nor host rock can be at risk from rock burst
7. No evidence can be found in sanctioned literature that raises doubts as to whether the minimum requirements with respect to hydraulic conductivity, thickness, and extent of the isolating rock zone can be maintained over the one million year prescribed safety interval

2.5.3.3 Favorability Criteria for Preliminary Investigation (Step 2)

Favorability criteria will be used during Step 2 to forward three to five highly probable repository-development (regional) areas to the site-scale assessments (socio-economic; repository design; surface and later subsurface geoscientific and mining exploration) performed in Step 3. Issues are grouped into *Weighting Groups* (1-3), with Weighting Group 1 considered most important and Weighting Group 3 the least. The geoscientific criteria are generally related to the exclusion criteria and minimum requirements, but discrete assessment parameters (e.g., measured/assigned hydraulic conductivity) are classified into (i) favorable, (ii) relatively favorable, or (iii) less favorable based on numerical values. Note that AkEnd's system does not provide for a summary numeric for a given favorability ranking within a specific criteria associated with a Weighting Group, nor does it assign a quantitative metric for comparing criteria within a Weighting Group relative to each other. Table 5 shows AkEnd's summary description of the Weighting Groups used in its overall geological setting assessment.

Many of these criteria are related to flow and transport phenomena and thus require extensive hydraulic characterization (or the ability to be characterized in later steps) at multiple scale lengths. Note that AkEnd has specified several assessment parameters based on the dominant rock types (salt, clay, and granite) they anticipate will be available following Step 1.

Table 5 − Weighting Group descriptions.

Weighting Group 1 **Quality of the Isolation Capacity and Reliability of Proof**	**Weighting Group 2** **Assurance of Isolation Capacity**	**Weighting Group 3** **Other Safety-Relevant Characteristics**
No or slow groundwater transport at repository level	Favorable rock-mechanic conditions are related to construction and management of the repository	Favorable conditions to control gas generation
Favorable configuration of host rock: large distances and travel times to biosphere, substantial barrier in case engineered structures fail.	Low probability of new flow-paths developing over time due to tectonic stresses	Favorable thermo-mechanical conditions in host rock
Ability to be spatially characterized: high reliability, low exploration effort / costs		High radionuclide retention capacity (sorption)
Good predictability		Favorable hydrogeochemical conditions to reduce release and transport of radionuclides

2.5.4 Issues Remaining to Be Answered

The most pressing question is when Phase II will be completed. At present, no consensus has been reached across the political landscape, with significant differences existing between the nuclear power industry and the government over key issues such as:

- Reimbursement of expenses incurred by the nuclear industry during the previous site selection and geoscientific exploration campaign at Gorleben
- Internet reports indicate that the nuclear industry, at least up through late 2004, were set against the AkEnd proposal in its entirety. In their view, no credible scientific evidence had been shown to suggest safety or other issues with Gorleben and collectively the industry was balking at the expenses they would incur should another selection process go forward
- With regard to practicality of implementation, concern about data availability and quality that would ensure a legitimate assessment during Step 2 was discussed by AkEnd itself. The specificity of the Weighting Factor criteria may not be achievable, and there could be legal issues later in the process if areas that are set aside because of data availability are subsequently shown to be superior to sites that do move forward. AkEnd did conceptually provide for an iterative process when necessary, but did not account for the implementation of that process.

Many additional problems, or likely problematic situations, arise in AkEnd's plan in Steps 3-5 due to the required public involvement and staged referenda built into the procedure.

2.5.5 Comparison to NUMO's Site Selection Process

The practical components of the selection processes developed (or suggested, in the case of Germany) by AkEnd and NUMO are strikingly similar with regard to (i) key procedural steps, and (ii) delineation of *exclusion* and *favorability* factors, that will move a possible regional area to a viable site investigation.

2.5.5.1 General Characteristics

NUMO has configured their process in one step, namely the PIA-to-DIA decision. AkEnd proposes to complete this work in two steps (Step 1 and 2, respectively). With regard to exclusion criteria, both NUMO and AkEnd focus on large-scale tectonic complications (fault location; volcanism during the quaternary; large vertical motions of geologic strata due to rapid uplift or erosion). AkEnd has specified an evaluation methodology, with assessment metrics, on the favorability factors that are reviewed in Step 2. In both nations, a technical/scientific panel—composed either directly (NUMO) or indirectly (in Germany) by the respective federal governments—will have oversight of the regional assessments, with planned public involvement included only at prescribed stages in the evaluations. A major difference in the two countries' approach is in how the PIA/Regional locales are selected for consideration in the process at the outset. In Japan, the process is organized around volunteerism, with host municipalities electing to participate through a formal solicitation response. In Germany, the process is supposed to start with a 'white map' of the entire country (modified by *a priori* excluded regions based on large-scale tectonic factors) with the implementing panel tasked with formal review of possible regions.

2.5.5.2 Interaction with Public

With regard to public interaction, the initiation policy appears to have a significant impact on the direct public involvement planned in the later steps of the selection process (DIA and forward in Japan; Steps 3-5 in Germany). Through self-nomination, Japan's strategy to engage the public pushes the public into making known, its willingness to participate at the very beginning.

Germany, on the other hand, proposes to use extensive referenda at a number of points in the site-forwarding steps to ascertain the willingness of its electorate to support further study and possible siting in a given area. The proposed policy ultimately refers any stalemate to the federal elected bodies to clarify and/or decide the way forward (or move to a previous step and regroup).

2.5.5.3 Distribution of Technical and Programmatic Information

In general, Japan and Germany have undertaken extensive public relationship-building exercises to supplement the technical aspects of repository site selection. Both have released simplified and detailed descriptions of the selection process and its components well before any actual evaluation has begun. AkEnd has proposed a formal structure for this dissemination (AkEnd, 2002), and how information is supposed to cycle between the public and implementation panel through the process.

2.6 Great Britain

The United Kingdom has not made a decision regarding its long-term (>50 years) HLW policy. Currently, spent fuel is temporarily housed at each power reactor site until temperatures have abated and shipment to the reprocessing plants at Sellafield can take place. HLW produced during reprocessing is housed (possibly vitrified) in surface facilities at Sellafield until a permanent repository is available. The only site selection procedure in the UK (1987-1991), developed for heat-generating non-HLW (or ILW), failed to produce even the planned Repository Characterisation Facility (RCF) at Sellafield. Following this setback, the UK government, in 2001, chartered the Department for Environment, Food, and Rural Affairs (Defra) to provide a comprehensive consultation on the issues and potential paths forward related to radioactive waste management (RWM). A politically independent panel, the Committee on Radioactive Waste Management (CoRWM), was appointed by Defra in November 2003 to: 1) develop, oversee, and scrupulously document a formal public review of all long-term radioactive material handling options, and 2) recommend the socially-optimal waste management strategy that will move forward in the implementation phase.

Implementation policy, including the definition of the site selection procedure, is to be determined by an as-yet unformed independent panel, following CoRWM recommendation and government acceptance of the disposal (i.e., repository construct) policy.

At this time, the outcome of the UK RWM strategy and site selection processes is not clearly documented. CoRWM will publish their policy recommendation, including their preferred strategy for linking short- and long-term storage and disposal combinations to handle the various (up to 600) waste streams, in July 2006. Implementation policy development, particularly the definition of the site selection procedure and site safety criteria, is anticipated to be completed by the end of 2007.

In the next two sections, a review of the CoRWM policy development procedure and the failed ILW repository siting at Sellafield are offered. The sections that follow discuss the UK management experience as it might inform the endeavors undertaken by NUMO.

2.6.1 CoRWM's Policy Development

Rather than starting with a scientifically-prescribed repository construct, CoRWM opened its initial policy considerations to all physical disposal options. Through a series of public citizen/stakeholder/specialist review meetings, a list of legitimate (i.e., supported by the majority of the participants) options were tabulated for further consideration. Three repository-type categories, with a total of 14 sub-options, have been selected including: long-term interim storage; geological disposal; and non-geological disposal. Through a series of workshops (June-December, 2005), a formal multi-criteria decision analysis (MCDA) scheme was designed and parameterized to quantitatively assess each repository construct relative to 11 criteria (with a total of 23 sub-criteria) for 7 different waste categories that typify the UK nuclear waste inventory.

Sub-Criterion 1: Public Safety – Short Term (up to 300y): Radiation
Specialist Scores for all Waste Streams

OPTIONS	MATERIAL/WASTE CATEGORIES						
	SNF/HLW		Pu	HEU	RDW	Other materials & wastes	
	SNF	HLW	Pu	HEU	ILW/non Drigg LLW	D, N, LE Uranium	ILW/non Drigg LLW
1	5	5	5*	8	5†	8	3
2	5	5	5*	8	5†	8	3
3	6	6	6*	8	6†	8	4
4	6	6	6*	8	6†	8	4
5	4	4	4	8	5†	8	3
6	4 to 6	4 to 6	4 to 6	8	5†	8	3
7	9	9	9	9	9	9	9
8	8	8	8	9	-	-	-
9	8 KBS-3 6 CARE	8 KBS-3 6 CARE	8 KBS-3 6 CARE	8	6	8	5
10	-	-	-	-	7 to 8	-	-
11	-	-	-	-	8 to 7	-	-
12	-	-	-	-	7	-	-
13	-	-	-	-	9	-	-
14	-	-	-	-	8	-	-

Figure 2 - Excerpt from CoRWM (2006c) showing an example of the MCDA Specialist scoring for one sub-criteria (short-term radiation safety) for all options (1-6: long-term interim storage; 7-9: geological disposal) for all waste streams. The scoring system is designed to show *higher* safety factors with *increasing* numbers.

Two figures (Figure 2 and Figure 3) are included to illustrate the MCDA system employed by CoRWM. These are shown to exemplify how such a procedure can be implemented. The site selection process that the UK will follow in the next two years will likely employ this type of objective-based metric when making the regional-to-site investigation decisions. Indeed, the development of the regional and site selection criteria may itself be subjected to such a process to enable the as-yet unformed panel a methodology to legitimately trade off scientific and social constraints. Figure 2 presents the tabulated scores, from Specialist Workshops, for short-term radiation safety for each sub-option for each waste stream. Figure 3 presents the MCDA outcome from the Specialist Workshops organized by sub-criteria and disposal sub-option for the HLW category. The decision space defined by CoRWM's analytic framework is clearly complex. The final development of their methodology is to define the relative weights associated with each waste type (if CoRWM considers a co-located, multi-waste facility as a possible engineered system) and sub-criteria so that an integrated score and subsequent rank can be assigned to a given sub-option (CoRWM, 2006b). CoRWM expects to have this process completed, with draft recommendations out to the public, by May 2006. The final recommendation to the government, incorporating feedback through June, is due in July 2006.

TABLE 2: HIGH LEVEL WASTE

		LONG TERM INTERIM STORAGE						GEOLOGICAL DISPOSAL			NON-GEOLOGICAL DISPOSAL				
HEADLINE CRITERIA	**SUB-CRITERIA**	Above grnd, local, current protection	Above grnd, central, current ptcn	Above grnd, local, enhnced ptcn	Above grnd, central, enhnced ptcn	Under-ground local	Under-ground central	Geolog Disposl	Bore hole	Phased geolog disposal	Near surface, local	Near surface, central	Mound over reactors	Shallow vault, central	Shallow vault, local
SAFETY, SHORT TERM	Radiation	5	5	6	6	4	4-6	9	8	KBS3-8 CARE-6	-	-	-	-	-
	Non radiation	**9**	**2**	**8**	**2**	**9**	**2**	**1**	**8**	**1**	-	-	-	-	-
SAFETY, LONG TERM	Radiation	-	-	-	-	-	-	9	9	KBS3-9	-	-	-	-	-
WORKER SAFETY	**Radiation**	**6**	**6**	**6**	**6**	**6**	**6**	**8**	**8**	**7**	-	-	-	-	-
	Non radiation	**3-5**	**3-5**	**3-5**	**3-5**	**2**	**2**	**1**	**2**	**1**	-	-	-	-	-
SECURITY	Missapprop	6-7	6-7	6-7	6-7	6-7	6-7	8-9	8-9	8-9	-	-	-	-	-
	Attack, pre-emplc	**8**	**4**	**9**	**5**	**9**	**5**	**3**	**2**	**1**	-	-	-	-	-
	Attack post-emplc	NA	2-4	NA	3-6	NA	4-8	7-9	7-9	7-8	-	-	-	-	-
ENVIRONMENT	Rad poll short	1	2	2	3	4	5	9	9	8	-	-	-	-	-
	Rad poll long term	-	-	-	-	-	-	7-8	9	7-8	-	-	-	-	-
	Chem. pollution	7	6-7	7	6-7	7	6-7	2	3-7	1	-	-	-	-	-
	Physical Disturbance	**4**	**3**	**4**	**3**	**2**	**1-3**	**6**	**7**	**4**	-	-	-	-	-
	Use of resources	**7**	**7**	**7**	**7**	**7**	**7**	**6**	**8**	-	-	-	-	-	-
SOCIO-ECONOMIC	**Employment**	**1**	**1**	**1**	**1**	**1**	**1**	**6**	**5**	**8**	-	-	-	-	-
	Spin-off	**2**	**2**	**4**	**4**	**5**	**5**	**7**	**9**	**8**	-	-	-	-	-
AMENITY	Visual	6	6	5	5	7	7	8	4	6	-	-	-	-	-
	Noise	**6**	**1**	**6**	**1**	**6**	**3**	**5**	**1**	**4**	-	-	-	-	-
	Transport	**7**	**4**	**7**	**4**	**7**	**4**	**4**	**1**	**1**	-	-	-	-	-
	Land take	**9**	**6-9**	**9**	**6-9**	**9**	**8**	**8**	**1**	**7-8**	-	-	-	-	-
BURDEN ON FUTURE GENERATIONS	**Cost**	**1**	**1**	**1**	**1**	**1**	**1**	**9**	**9**	**7**	-	-	-	-	-
	Effort	**1**	**1**	**1**	**1**	**1**	**1**	**9**	**9**	**8-5**	-	-	-	-	-
	Worker dose	**1**	**1**	**1**	**1**	**1**	**1**	**9**	**9**	**7**	-	-	-	-	-
	Environment Impacts	**1**	**1**	**1**	**1**	**1**	**1**	**9**	**9**	**9**	-	-	-	-	-
IMPLEMENT-ABILITY	**Technical**	**7**	**7**	**4**	**4**	**7**	**7**	**5**	**1**	**4**	-	-	-	-	-
	Legal & Regulatory	**8**	**8**	**8**	**8**	**6**	**6**	**5**	**3**	**5**	-	-	-	-	-
FLEXIBILITY	**Flexibility**	**8**	**8**	**8**	**8**	**8**	**8**	**3**	**1**	**8-9**	-	-	-	-	-
COST (£BN, across all wastes)	**Cost Estimate Low - high**	**17 9-27**	**9 7-14**	**20 12-30**	**12 10-17**	**17 9-27**	**9 7-14**	**11.3 10-18**	**4.6 3-18**	**13.2 12-21**					

Bold = score is the same (or almost the same) for every waste stream. All others = significant differences in scores between waste streams.

Figure 3 - Excerpt from CoRWM (CoRWM, 2006a) showing an example of the Specialist scoring results associated with HLW, for all sub-options and each sub-criteria.

As the RWM policy recommendation deadline draws close, the scientific community, particularly The Royal Society, has expressed concerns about both the ongoing efforts of CoRWM and the need to begin to define the parameters of the implementation phase (Royal Society, 2006). Their primary issues relate to:

- the artificial distinctions made by CoRWM when defining the sub-options as mutually-exclusive, as they believe that any valid management plan will necessarily include storage and probably adaptive phased geological disposal
- the exclusion of implementation constraints as prominent factors in the determination of the management strategy itself
- the general understatement of safety confidence that can be demonstrably assigned to geological disposal programs

In fact, The Royal Society has proposed an overarching principle for any new site selection process: “A criterion for site selection should be the capacity to demonstrate, from geological evidence, the stability and integrity of the site over a past timescale significantly greater than the required isolation periods of wastes to be disposed” (Royal Society, 2006).

2.6.2 The Early Geological Disposal Program

To date, the UK has been unsuccessful in previous attempts to deal with non-low level waste (LLW). All ILW and HLW are currently housed in surface containment structures at reprocessing plants or at the site of radioactive waste generation, waiting final packaging prior to disposal. The organization tasked with LLW/ILW disposal, United Kingdom Nirex Limited (Nirex), has itself been transformed following the Defra consultation and appointment of CoRWM. Nirex was originally formed in 1982 as a quasi-industrial entity but, in April 2005, became an independent company as it was believed that such a change would fundamentally alter the public perception of its work and lend credibility in its role as government adviser, scientific research institute, and regulator of waste packaging protocols. It is unclear what organization will oversee the HLW packaging and engineering oversight, but it is possible that Nirex will be expanded to fill this role once the RWM strategy is determined by the government following CoRWM's recommendation.

With any guidance regarding site selection from the implementation phase of the UK governments reorganization of RWM still more than a year away, only a review of past efforts at disposal can be undertaken to provide a background on how the site selection process may look, and what might be the possible site selection criteria used to decide where detailed characterizations may take place. Between 1987 and 1991, Nirex embarked on the only previous attempt to select a repository site for any heat-generating radioactive waste. The selection of Sellafield as the strongest locale for further deep geological disposal research (at the Rock Characterisation Facility, or RCF) failed during the attempt to obtain a license from the local government (in 1994), a decision that was upheld by the Secretary of State for the Environment in 1997. Prior to June 2005, the process that was followed during the site selection review, the selection criteria employed, and even the names of the sites reviewed at each step, was unknown except for the two final sites (Dounreay and Sellafield, respectively). The following section provides a summary of the process as reported by Nirex.

2.6.2.1 Review of 1987–1991 Site Selection for an ILW/LLW Repository

Nirex approached site selection following general guidelines provided by the International Atomic Energy Agency (IAEA). This guidance included:

- repository site selection should be based on a balanced analysis of geological, ecological, and societal considerations
- utilize a progressive, staged evaluation process
- site selection (where detailed subsurface geoscientific exploration is to be conducted) should be integrated with repository concepts and design to ensure proper inclusion of engineered barriers in the long-term site performance assessment

Nirex set up a three-staged sequential selection process including

- <u>Regional Area</u>: selection based principally on broad hydrogeologic guidelines and governmental or nuclear industry shareholder land ownership
- <u>Site Identification</u>: comparative evaluation to identify outstanding candidates for given hydrogeologic environments, for further geoscientific exploration
- <u>Site Confirmation</u>: detailed characterization efforts and application of multi-attribute decision analysis (MADA) to objectively determine and rank the selection of ~3 final sites

Attributes were effectively grouped into five assessment categories described in Table 6. In terms of preliminary and detailed geoscientific screening, the principal characteristics of the region or site related to the hydrogeologic environment rather than specific lithologies (Table 7). These definitions were provided by the British Geological Survey (BGS).

Table 6 − Assessment criteria

Category	***Description***
Safety	pre- and post-closure periods; conventional and radiological issues for repository and transportation workers, and general public
Socio-economic and environmental impact	potential environmental degradation; planning and conservation issues relative to potential harm of repository development
Transportation	distance and associated risk evaluations; design considerations
Robustness	extent to which overall evaluation of site could be sustained and verified, particularly with respect to preliminary geologic descriptions and ability to test against data from future geological investigations
Costs	capital investment during construction phase; operation expenses of repository and transportation system

Table 7 − Hydrogeological environments.

Environment	***General synopsis***
hard rocks in low-relief terrain	minimal driving potential for fluid flow
low permeability basement under sedimentary cover	regional groundwater flow in sedimentary (rock) cover with little connection to underlying basement
seaward-dipping offshore sediments	groundwater flow is slow and under coastline
inland mixed sedimentary rock basins	possibly stagnant groundwater systems (generally disregarded because of complexity)
small islands	groundwater beneath seawater/freshwater interface is stagnant

The Regional Area selection yielded 537 locations for consideration, principally on land owned by the government or nuclear industry shareholders but with a few volunteered possibilities offered by private landowners. Reduction to a short list forwarded to the second stage, Site Identification, followed a six-step review. These steps included:

- *initial screening*: geologic and planning considerations
  number forwarded: **204** number eliminated: 333
- *land ownership*: all sites not in public domain, excepting a few volunteered sites, were eliminated
  number forwarded: **165** number eliminated: 39

- *site size*: adequacy of site given required land-take for surface infrastructure and underground repository
  number forwarded: **117** number eliminated: 48
- *geologic evaluation*: detailed re-examination by BGS
  number forwarded: **39** number eliminated: 78
- *initial comparative evaluation*: generic assessments of radiological safety, geology, socio-economic, environmental issues, repository design concepts, and transportation processed through a MADA-type scoring system, with the goal of identifying the best 3 or 4 locations for each hydrogeological environment
  number forwarded: **17** number eliminated: 22
- *detailed comparative analysis*: additional assessments, especially with respect to radiological safety, were applied (Billington et al., 1990)
  number forwarded: **10** number eliminated: 7

The ten (10) sites passed into the Site Identification stage were processed through a formalized MADA tool developed at the London School of Economics and Political Science (LSE). The MADA was parameterized (methodology and weighting of score attributes) under the guidance of the LSE expert. The attributes were collectively contained in the previous delineation relevant to regional area assessment (Table 1 Categories). Ultimately, the costs and risks associated with transport strongly influenced the Nirex decision to forward Sellafield and Dounreay for parallel subsurface exploration in the Site Confirmation stage. Both sites would be in hard basement rock underlain by sedimentary cover. Sellafield was moved forward as the top priority for further research since approximately 60 % of the estimated waste was generated at the site.

In hindsight, Nirex believes several key missteps were the cause of the failure to move into the subsurface characterization phase planned at the RCF in Sellafield. Their self-assessment highlights process-oriented issues (rather than scientific credibility) including:

- The need to define, at the outset of the site selection process, *all* criteria, weighting, and analysis schemes through extensive public discourse with stakeholders
- The selection process should be open, meaning that new findings may lead in different directions of inquiry if accepted by the public
- During implementation, the technical review must be reported clearly and in a timely manner, with time included for public feedback to be incorporated into decision making *before* the next step is taken
- *All* decisions, and pertinent technical review or developments, must be appropriately documented and made available in a timely manner

2.6.3 Issues Remaining to be Answered

The UK is in the final stages of a RWM strategy formulation process, with key elements of the implementation stage completely undefined. Given the time line that CoRWM and the government appear to be working under, the formation of the independent panel (or re-chartering CoRWM) that will oversee the development of the site selection process should be announced before the end of 2006.

2.6.4 Comparison to NUMO’s Site Selection Process

Nirex's review of its previous site selection process also highlights advances in understanding since the 1987-1991 period that are particularly relevant to deep geological investigations, modeling, and natural process dynamics. These advancements will significantly change the data requirements and detailed evaluation efforts in the UK's upcoming site selection process. These include:

- 3D seismic survey acquisition and processing techniques
- computational technology, with respect to improved codes for modeling complex water/rock/fluid relationships and model domain size and resolution
- improvements in first-principle understanding of geologic barriers, e.g.
    - using geochemistry as an indicator of flow patterns, water/rock/fluid interaction, and isolation/containment properties of the subsurface
    - effects of climate change dynamics on surface and deep geological structures
    - paleohydrogeology used to unravel rate of change of groundwater flow and geochemical compositions due to changing geologic and climate forces

While such hydrogeological data types will not be directly used in the legal requirements that must be satisfied under NUMO's *Evaluation Factors for Qualification* during the PIA phase of the selection process, assessment of the Favorable Factors (and data used to verify such factors) will utilize the type of information contained in first-principle characterization improvements of geologic barriers above.

2.7 Spain

In Spain, high level wastes are understood to be the non-reprocessed spent fuel from nuclear reactors, with the exception of fuel from the Vandellós plant, which has been sent to France for reprocessing (LBNL, 1996). Thus there are two types of HLW's within Spain that need to be managed: 1) spent fuel from the countries light-water reactors, which comprises the bulk of the waste, and 2) the reprocessed, vitrified wastes from the Vandellós plant.

The Empresa Nacional de Residuos Radioactivos SA (ENRESA) was established in 1986 for the purpose of managing HLW as well as for designating a repository site. The strategy for the management of spent fuel and HLW in Spain is currently based on ensuring the availability of the scientific and technological know-how and capacity required for definitive disposal in deep geological formations, either granite or clay. However, as is described in more detail below, Spain's program for choosing a specific site has been postponed until 2010.

2.7.1 General Site Geology

In 1987, ENRESA began searching for favorable rock formations in salt, clay, and crystalline environments with the hopes that an operating repository site would be realized by the year 2025. A 'National Inventory of Favourable Formations' project (IFA project) was developed in 1986-7 and a selection process known as the 'High Level Regional Studies' (ERA project) was developed (LBNL, 1996). The site screening project was based on geological, hydrogeological, seismic, environmental, and societal data. Within 3 years of the start of the program, approximately 25,000 km^2 of possible regions were found and out of that, 30 areas were identified for further research (van den Berg and Damveld, 2000). However, public opposition halted the repository location efforts in 1996 after ENRESA released a list of possible locations to the public. Environmental and public activist groups accused ENRESA of not properly informing the public and of having privately inspected the possible sites.

Prior to the postponement decision, preliminary conceptual designs were completed for salt, clay, and crystalline rocks (ENRESA, 1995). Since that time, probabilistic performance assessments in generic granite and clay formations have been completed (Lidskog and Andersson, 2002). As of 2003, ENRESA was participating in 3 different repository projects in Sweden (Äspö), in a number of projects in the two laboratories in Switzerland (Grimsel Test Site and Mont Terri), in projects in the Belgian Mol Site, as well as in the Meuse/Haute-Marne laboratory in France (Markova, 2003). The distinguishing factor of all these studies is that they specifically address repository development when the host rock is either clay or granite (LBNL, 2001). In addition, other current R&D efforts have focused on the generic design of an underground storage facility within these lithologies due to the fact that ample representation of these lithologies exist within the country and thus there is a high potential of a repository being located in one of these environments (ENRESA, 2004).

2.7.2 Status of Site Selection

Since its inception in 1986, ENRESA has been carrying out its HLW repository R&D through a series of five-year plans, the most recent of which covers the period 2004−2008 (ENRESA, 2004). The initial plan, which was put in place in 1986, was specific with regards to the strategy of management of the HLW's and contained defined landmarks over time; but it contained no consideration for revision in the face of unknown difficulties. This strategy was to select several candidate locations by 2000 that would be characterized in detail through 2015, at which point the final location would be chosen. The intent was to have a functioning repository by 2025. The R&D was oriented towards obtaining a set of technologies and methodologies that would allow for the detailed characterization of locations, as well as the design, construction, and verification of the operation of the engineered barriers. In light of strong public opposition to this plan, the strategy was modified in 1996/1997. This new strategy established a period until 2010 for the generation of knowledge, study of options, and completion of research that included both underground storage of the HLW's as well as separation and transmutation. Part of this strategy stipulated that specific site investigations (e.g. drilling) could only occur after the 2010 deadline and that a voluntary process had to be 'expected' before these studies could take place (ENRESA, 1999a). This meant that current characterization studies could only continue with existing data and/or as non-site specific research. As a response to this new strategy, the Spanish Senate Commission for Industry established an inquiry commission to develop a new waste policy (as separate from the R&D strategy). The goal of the commission was to study the difficulties of finding a waste disposal site while incorporating the socio-political and public acceptance aspects. The outcome of the commissions work was to be a set of guidelines for the government to develop a legal framework for siting. This period from 1986 to 1995 represented Phases I and II of ENRESA R&D work (ENRESA, 2004).

Phase III is stipulated to be from 1995−1999. The main difference between Phase III and Phases I and II is that Phase III places a higher importance on integrating the Spanish efforts with the underground laboratories and programs of the European Union (EU). Within this Phase, the FEBEX project (part of the Grimsel Test Site) was begun and is being led by ENRESA as a world-wide effort for the purpose of performing *in situ* engineered barrier research. Additionally, this phase began research into argillaceous rock storage, through participation in the underground laboratory of TM Terri (Swiss).

Phase IV (1999−2003) was used to verify existing work involving granite technologies while beginning research into clay technologies. For their granite studies, research was conducted as part of the restoration process of old uranium mines, with the intent of developing generic approaches into the characterization and operation of a facility within a granite lithology (Escuder-Viruete et al., 2001; 2003a; 2003b; 2004; Gómez et al., 2001; 2006; Pérez del Villar et al., 2002; 2003). It was within this stage that the Spanish began to obtain a database on the processes and parameters for the long-term storage of HLW with respect to the durability, hydrogeology, hydrogeochemistry, geomechanics, and the transport and migration of radionuclides. In addition, the development of new models, and the maturation and verification of older models was also addressed with the intent of developing generic technologies of characterization related to the construction and monitoring of a HLW repository.

The current Phase (2004-2008) builds on the work of Phase IV, with an emphasis of forming international collaborations. As mentioned above, it is during this phase that ENRESA expanded its international work such that they are participating in 3 different repository projects in Sweden (Äspö), in a number of projects in the two laboratories in Switzerland (Grimsel Test Site and TM Terri), in projects in the Belgian Mol Site, as well as in the Meuse/Haute-Marne laboratory in France (Markova, 2003). Most of this work involves projects of characterization of the hydrogeology and geochemistry of a generic crystalline rock, as well as tests involving the filling and sealing operations of a storage gallery. At this time, ENRESA still has not undertaken R&D involving the construction and operation aspects of a repository nor has one design approach been favored over another, mainly due to the fact that the actual location of the repository is still unknown. The overlying intent of the current approach, even though it is at a generic level, is that in 2010 when the site selection process begins in earnest, ENRESA will be able to greatly reduce the selection time by taking advantage of the synergy and collaborations with other similar organizations, as well as by adapting their generic approaches to a specific site.

2.7.3 Flow and Transport Data

Given the generic nature of the Spanish repository effort, studies pertaining to a specific site with regards to site characterization are not available. However, many studies have been conducted within the Spanish program that are meant to test different characterization approaches or to develop new approaches given limited amounts of data. This section will present several of the more pertinent Spanish studies that may be applicable to Japan and to NUMO's site selection process. This section will summarize those studies, with the following sections addressing more detailed aspects of each study that are in line with the objectives of this review. All of these studies with the exception of one, were either funded by, or associated with ENRESA.

Escuder-Viruete et al. (2001; 2003a; 2003b; 2004) have completed a series of studies involving the Albala Granitic Pluton, that is part of the SW Iberian Massif in Spain. While these studies are more local in nature (the study area is on the order of one square kilometer), they do provide good examples of characterization with limited and disparate types of data. The first of these studies (Escuder-Viruete et al., 2001) applies geostatistical methods to data from formation outcrops to map fracture index (FI) across the region. The FI is a quantitative definition of the fracture density that describes the decrease of the fracture density as one moves away from the central fault core (e.g. Gillespie et al., 1993). The main objective of this study was to test whether the FI distribution obtained from the geostatistical modeling characterizes quantitatively, the fracture system in two-dimensions. Utilizing 115 FI measurements, Escuder-Viruete et al. (2001) use directional variograms to krige the data across the 1 km square study zone. This map is then super-imposed by a map of know faults in the region. The obtained distribution of the FI and their correlation to the known faults, permits them to distinguish two structural zones; elongated bands of fracture zones and rhomboidal blocks located between them. The final conclusion is that constructing maps of the FI in this manner permits the quantitative structural classification of the rock massif, at least for strike-slip zones in brittle formations.

The second study on the Mina Ratones area by Escuder-Viruete et al. (2003a) is similar to the first study (Escuder-Viruete et al., 2001) with the exception that they incorporate FI measurements from four boreholes within the study zone and that they extend the geostatistical analysis to 3D. The extension to 3D results in a cell-based spatial distribution of FI where each cell has a single FI value. As per the first two studies, this method proved valuable in identifying blocks of less-fractured granite surrounded by bands of high-fracture zones. The results compare well to seismic profiles, well-core structural analysis, and detailed structural maps of the area.

Escuder-Viruete et al. (2003b) then build on these studies by integrating geological and geophysical data to form a 3D structural map of the Mina Ratones area of the Albala Granitic Pluton in SW Spain. This study attempts to quantify the link between the lithology of a geologic site, its structure, and its seismic properties. This study provides a useful example of linking hard (field core and well-log data) and soft (seismic tomographic data) data. For the Mina Ratones area, the geology is lithologically characterized by cataclastic fault rocks, an increase in brittle micro-structural deformation, and the development of geo-chemical alteration. The higher concentration of fractures, faults, and veins results in zones of lower seismic velocities relative to the protolith (Escuder-Viruete et al., 2003b). The spatial relationships are then expressed through standard variograms and then combined with the hard data using the method of stochastic conditional co-simulation of two-variables (Deutsch and Journel, 1992; Gómez-Hernández and Srivastava, 1989). The results are presented as a possible image of the fault-zone architecture that honors both the hard and soft data, and a probabilistic and quantitative 3D model of spatially heterogeneous fault-zones that are on a suitable scale for groundwater flow modeling. The fault-zone model and the architecture image are both consistent with previous conceptualizations of the massif. Like the earlier study (Escuder-Viruete et al., 2001), this study identified bands of faults whose intersections define rhombohedral blocks of relatively less-fractured granite.

Lastly, Escuder-Viruete et al. (2004) use the distribution of fault-rocks, brittle structures, deformation mechanisms, whole-rock geochemistry, and changes in the P- and S-wave seismic velocities across a local fault feature (the North Fault) to construct a 3D model of the fault structure using geostatistical methods. Geochemical, microstructural, and mineralogical variations within the fault zone are also interpreted. Much of this study is based on site-specific data from the microscopic scale to tens of meters but can be extrapolated to larger scales for use in regional 3D fault zone modeling for use in groundwater flow models. Specifically, Escuder-Viruete et al. (2004) use the finer scale observations and analysis to derive the spatial correlation between the fault-rock development, high FI values, and low seismic velocities. Similar to the methods in Escuder-Viruete et al. (2003a), this information is then used to construct a 3D fault-zone model of the larger area.

More recently, Gómez et al. (2006) published the results of a comparative study that examined the hydrogeochemical characterization of different rock types (granite and schist) up to 500 m in depth. Specifically, they looked at abandoned uranium mines located in the Central-Iberian Zone of the Hesperian Massif and the characterization of three sites: 1) El Berrocal (Toledo), which is a granite pluton with a high fracture density and strong hydraulic gradients, 2) Los Ratones (Cáceres), which is also a granitic pluton but acts as a discharge zone of the surrounding mountain range, and 3) Sageras-Mina Fe (Salamanca), which is a highly fractured schistose rock where the recharge comes from the surrounding mountains and discharge occurs in the nearby Águeda and Yeltes rivers. The findings showed that the main water-rock reaction processes responsible for the groundwater characteristics at the three sites consist of alteration of silicates, dissolution/precipitation of carbonates, and ionic exchange. The main output of the study is a conceptual model that accounts for these processes while accounting for the local flow system. Despite the hydrogeological differences between the three sites, Gómez et al. (2006) found that dilute Ca-HCO_3 type waters with modern levels of ^3H are located in the upper parts of each site. With increasing depth, the waters evolve to Na-Ca-HCO_3 type waters with reducing and Na-HCO_3 type waters found in the deepest depths (> 400m). They also found that the dissolution of carbonate-cemented (ankeritic) rocks and the precipitation of siderite control the Fe^{2+} and HCO_3^- concentrations. Ion exchange processes with smectites in the fracture fillings control the concentrations of Ca^{2+}, Mg^{2+}, and Na^+.

In comparing their work to similar studies in Europe, Canada, and Japan (Edmunds and Savage, 1991; Gascoyne, 2004; Gascoyne and Kamineni, 1994; Iwatsuki and Yoshida, 1999; Laaksoharju, 1999), Gómez et al. (2006) conclude that the chemical composition of the groundwater is highly dependent on the geological history of each area, which determines the chemical evolution as well. They showed that the Spanish groundwaters have similar chemical compositions to those of the Toki granite in Japan and the Grimsel granite in Switzerland, but are different from the Canadian or Scandinavian Shields and Carnmenellis groundwaters. Therefore, investigations concerning the deep geologic disposal of radioactive waste need to account for local conditions at each site with specific attention paid to the chemistry of the recharge water, the main dissolution and precipitation constituents, as well as the minerals within the fractured zones that control the ion exchange reactions.

Another Spanish led study (Alonso et al., 2006) looks at the role of inorganic colloids in the migration of radionuclides. Funded by the European Nuclear Structure research program and the Spanish Ministry for Education and Science, the study serves as a review of research that examines the colloid contribution to radionuclide migration within a crystalline rock environment. Much of the study examines the near-field aspects of colloid transport but considerable discussion is given to far-field issues. In addition, Alonso et al. (2006) identify areas of uncertainty and give suggestions for future research that would most directly address those areas. They conclude that there are two main pathways in which colloid research should proceed: 1) determine and identify the underlying mechanisms of colloid-radionuclide and colloid-rock interaction, and 2) perform radionuclide and colloid migration studies under relevant (i.e., host-rock) conditions. They also surmise that three main uncertainties exist and that without reducing this uncertainty, overly conservative estimates must be used when assessing a particular site. Those three uncertainties are: 1) the question of quantifying colloid generation under realistic repository conditions, 2) questions surrounding the mechanism of radionuclide sorption onto bentonite colloids and rock surfaces at enhanced contact times, and 3) the quantification of colloid filtration mechanisms acting in a natural system. Finally, they suggest that to address these uncertainties, a close collaboration must exist between the modeling and experimental groups in order to define the models requirements (i.e. the needed input parameters) while adequately forming the experimental work.

2.7.4 Identified Parameters

The representative studies presented above concentrate on characterization of fractured environments in brittle, strike-slip lithology, the hydrogeochemical characterization of groundwater in two different rock types (granite and schist), and the role of colloid contribution to radionuclide migration. From these studies, several parameters are specifically discussed or highlighted that may be of use for characterization at the regional scale. Those parameters are summarized in Table 8 below.

2.7.5 Data Collected During Site Selection

The current ENRESA five-year plan allows only for generic studies in designated, *in situ* research facilities or with data that have been previously collected. Thus, no data collection program exists at this time that is part of a regional site-selection process. Data utilized in the above summarized studies include surface observations of rock outcrops, borehole core analysis, well-log data, seismic tomographic data, various forms of chemical analysis (chemical composition evaluation), and geologic observational data.

2.7.6 Data Collection Methods

With the exception of the quantification of colloid populations in natural groundwaters, none of the data utilized by the Spanish program relied on specialized and/or new collection techniques. However, with respect to natural colloid populations, Alonzo et al. (2006) suggest that optimum characterization of colloids requires the application of *in situ* characterization techniques since colloid concentrations are extremely sensitive to sampling and sampling storage, and that concentrations are often below detection limits. One innovative technique that has been recently developed for this purpose is the Laser-Induced Breakdown Detection (LIBD) that exhibits a very high sensitivity for the detection of colloids, being many magnitudes better than light-scattering methods, especially for particle sizes of < 50 nm (Hauser et al., 2002; Hauser et al., 2003; Walther et al., 2002). Other techniques such as Flow Field-Flow Fractionation (FIF-FF) combined with different detection modes (Geckeis et al., 2003; Gimbert et al., 2003) or the Single Particle Inductively Coupled Plasma-Mass Spectroscopy (Degueldre and Favarger, 2003) have also shown promise in this area.

Table 8 − Relevant parameters that were studied through selected Spanish research.

Parameter	Context	Application	Dependent parameters
Fracture Index (FI)	Strike-slip fault zone within a granitic pluton	Kriged and co-kriged (with seismic tomographic data) to develop 2D and 3D maps of the fracture environment. Matched against known fault maps, the kriged distributions provide a way to statistically fill-in structure where data do not exist	High correlation between FI and transmissivity (i.e. permeability)
Seismic tomographic data	Strike-slip fault zone within a granitic pluton	Co-kriged (with FI data) to develop 3D maps of the fracture environment. Matched against known fault maps, the kriged distributions provide a way to statistically fill-in structure where data do not exist	High correlation between FI and transmissivity (i.e. permeability). Negative correlation between FI and seismic wave velocities.
^{3}H and ^{14}C concentrations	Granitic pluton	Residence time of young (< 60yrs) and older (>60yrs) groundwater	Recharge rates, groundwater flow rates
Redox condition	Granitic pluton and schist	Solubility potential of radionuclides	Eh, pH, Bi-carbonate and cation concentrations
Colloid sorption reaction rates	Crystalline rock	Radionuclide to rock and radionuclide to colloid	Enhanced radionuclide transport
Naturally occurring colloid concentrations	Crystalline rock	Characterization of background colloid environment to help with colloid transport assessment at the rock/bentonite interface	Contaminant migration, geochemical gradients, mechanical disturbances

2.7.7 Interpreted Importance of Active Tectonics

Within the studies examined for the Spanish ENRESA program, issues that take on added importance in an actively tectonic environment are those that pertain to geochemical evolution and colloid transport. Some of the geochemical characterizations presented by Gómez et al. (Gómez et al., 2006) are stated as being temperature dependent. The compositional variations of the major ions, pH and redox conditions, and water-rock reactions are all effected by changes in water temperature. It should be noted that this could include temperature changes to both the local environment, as well as at the recharge environment. With the exception of the mention of temperature dependency, no discussion is given as to the implications of these changes.

The colloid study by Alonso et al. (Alonso et al., 2006) also points to processes that are temperature dependent: sorption / desorption rates for radionuclide binding to both rock and colloids and the stability of colloids are two processes that are specifically identified as being temperature dependent. Additionally, the natural background concentration of colloids can be influenced by mechanical disturbances, indicating that colloid concentrations could be higher in tectonically active areas than in quiet areas. This could have a large impact on the mobility of radionuclides in the far-field. No research to date on this dependency was identified within the Spanish program.

2.7.8 Issues Remaining to be Answered

It is not clear how ENRESA will begin their site-selection process come 2010. The 2003-2008 operational plan (ENRESA, 2004) does not provide a means for assuaging the public fears that originally postponed the process in 1996. The hope is that by 2010, they will have built up a better scientific understanding of the issues and that they can use that understanding, as well as the experiences of international programs, to help guide the selection process.

From a scientific point of view, current research appears to be focusing on near-field issues (at the drift-scale) and local-scale characterization issues (1-2 km scale), with most of these concentrating on understanding key physical properties that control radionuclide migration and flow-field characterization.

2.7.9 Comparison to NUMO's Site Selection Process

Since its inception in 1986, ENRESA has been carrying out its HLW repository R&D through a series of five-year plans, the most recent of which covers the period 2004-2008 (ENRESA, 2004). Each one of these plans is based on a step-wise approach, whereby all agents involved (technicians, politicians, public regulators, etc.) participate, and the different actions that are executed are the result of analysis and consensus amongst all involved. The criteria for the development of the step-wise methodology are based on the security, flexibility, and transparency of the process. This process insures that the program will not only integrate the technical activities, but the socio-economic activities as well (ENRESA, 2004). At present, the Spanish site-selection process can be described by the following priorities set for their R&D program:

- The necessity to develop science and technology that will propose specific actions of HLW management
- The necessity to verify, on suitable spatial and temporal scales, that the proposed actions of management are safe, technically viable, and economically feasible
- The necessity to acquire operative experience in the areas of improving and optimizing extensions or new facilities
- The necessity to develop and obtain numerical tools and methodologies to evaluate the long term security of the disposal site
- The necessity to reduce the uncertainties in the long-term operation of the repository and to improve or to contribute to the social acceptance of the solutions

Included in these priorities is the integration between technical knowledge and the social acceptance, which will require the formation of a set of performance standards with the R&D programs providing a forum for discussion, integration, and consensus.

2.7.10 Interaction with Public

ENRESA has set up four 'Information Centers' that are attached to each of their four main work centers. The objective of the ENRESA Information Centers is to bring the information handled by their scientists closer to the general public and in particular to young people. Visits to the centers are by appointment only and meant to be utilized as group tours.

In addition to the Information Centers, ENRESA has a permanent exhibition in the geology section of the National Natural History Museum of Madrid. The content of the exhibition is designed to complement the museums mission by discussing the isolation capacity of certain minerals and geological environments. The basis of the exhibition is to present the geological considerations associated with the deep burial of HLW.

2.7.11 Distribution of Technical and Programmatic Information

The 5th General Radioactive Waste Plan states specifically that, "any action in this field (siting of an underground disposal facility) will require the furthest reaching communications campaigns as possible, with a view to providing the public with whatever information might be necessary; this is especially important because of the high level of social sensitivity to issues relating to radioactive waste" (ENRESA, 1999a). In light of this statement, the 1998 Communication Plan was developed with two main areas of emphasis (Lidskog and Andersson, 2002): 1) Training / Information, and 2) Communication with the media.

Currently, ENRESA's strategic guidelines for information and communication are (INLA, 1999):

1. Wide, transparent, and true information to the different social sectors
2. Training on specific topics to university students working in related matters
3. To comply with regulations regarding the assignment of funds to the municipalities close to ENRESA installations
4. Cooperation with the local authorities to improve the resources and infrastructures of those areas surrounding ENRESA facilities.

Communication and relations with the media has also been a major effort, carried out mainly through news releases and reports. Seminars that include journalists participating in radio and television debates have also been used. It is agreed that the material released to the public via these means has been received positively by the majority of the people as well as approached positively by the various news media (ENRESA, 1999b).

ENRESA also maintains a well organized and up to date website that can be accessed by the general public (ENRESA, 2006). The website is presented in both Spanish and English and contains links to various document types (institutional reports, audiovisuals, publications, and legislation), current events (news releases, upcoming public events, and material for the press), and current and past projects. In addition, the Spanish programs have published numerous research papers in peer-reviewed scientific journals.

2.8 Sweden

The Swedish program for disposal of spent fuel, operated by Svensk Kärnbränlehantering AB (SKB) is, one of the world leaders regarding both documentation and the technical level of work done. SKB was founded in 1985, after extensive and contentious national debate concerning the future of both nuclear power and waste disposal in Sweden. This debate culminated in a national referendum in 1984. SKB is owned by the four power companies and is tasked with managing and disposing of radioactive waste from the Swedish nuclear power plants in a manner that complies with governmental standards. Currently, Sweden is managing their waste through a central interim storage facility, located in Clab, near Oskarshamn Municipality. The continuing plan calls for permanent disposal of un-reprocessed spent fuel in the crystalline rocks of the Baltic Shield.

SKB is focusing its characterization efforts on two potential sites, Forsmark and Oskarshamn (Simpevarp). Site investigations were begun in both Forsmark and Oskarshamn in the spring of 2002 with the work being divided into two stages: an initial and a complete site investigation. The results of the initial site investigation are to be compared with the previous assessments of the suitability of the areas. In addition, the initial site investigation is also to identify which of the proposed areas in Forsmark and Oskarshamn is judged to be most suitable for a final repository. The initial site investigations are scheduled to be concluded in the spring of 2006 for both sites and the results reported in preliminary site descriptions and safety reports.

As a general description, SKB has identified several factors that will guide and determine the suitability of a site. Those factors are:

- The industrial facility should be built on a site where the environmental impact is minimal
- The site must be easily accessible with no transportation problems
- The local residents and the municipality must be positively inclined towards locating the repository in their area

The bulk of the documentation considered in this review is taken from SKB Technical Reports. What follows is a general description of the initial site investigation efforts and some of their useful conclusions.

2.8.1 General Site Geology

The Swedish program is presently focused on two potential sites: a) Simpevarp; and b) Forsmark. Both sites lie on the Baltic shield, and are underlain by Precambrian igneous and high-grade metamorphic rocks, with incidental younger cover. The summary descriptions here are taken from recent pairs of documents, consisting of Preliminary Safety Evaluations (PSE's), and detailed Site Descriptive Models (SDM's) for the two site areas (SKB, 2005a; 2005b; 2005c; 2005d). A very good general reference on the structural geology and tectonics of SE Sweden appears in Milnes et al. (1998).

2.8.1.1 General Geology – Oskarshamn

The Oskarshamn characterization area has been divided into the Simpevarp and Laxemar sub-areas. Since the two sub-areas are essentially adjacent to each other, the geologic description summarized here applies to both. Although the rocks at Simpevarp can be broadly considered as crystalline rocks, the detailed geologic history indicates some of the complexity that can be encountered, even in such a stable area as the Baltic Shield. In summary, the local geologic history can be divided into two main sequences, the Svecokarelian Orogeny, extending from 1960 to 1750 mybp, and the history extending from 1750 mybp to the present (SKB, 2005d).

The Svecokarelian orogeny can be generally described as a period of alternating intrusive igneous activity, some sedimentary activity, and regional deformation at depth. The bedrock at Simpevarp has been subjected mainly to low-grade metamorphism combined with local ductile deformation. Since the Svecokarelian orogeny, the area has transitioned from ductile deformation to more brittle deformation, mainly in response to continued uplift and stabilization of the crust. This time is marked by alternating periods of brittle deformation and general subsidence, with the most recent history exhibiting post-glacial fault movement.

It appears that brittle faulting mainly occurs by means of reactivation of pre-existing ductile features (Bäckblom and Munier, 2002). It is interesting to note that 10 periods of possible local reactivation of these structures are identified over the recent time period (Munier, 1995). The most recent brittle deformation at the nearby Äspö Underground Research Laboratory (URL) appears to have occurred ~250 mybp. Thus, while there is abundant evidence of both activation and reactivation of ductile and brittle structures over long geologic time scales, it is information over the timescales associated with the storage of nuclear waste (~10^6 years or less) that is lacking.

SKB has made an extensive effort to estimate 'respect distances' from known deformation zones (i.e., distances, measured perpendicular to an identified major structural feature) within which no waste canister can be emplaced, based on the combination of models of secondary fracturing/faulting and requirements for emplacement-hole stability (no displacements larger than 0.1m) (Munier and Hökmark, 2004). The results of this study are based on a series of numerical assumptions, including a baseline earthquake of magnitude 6, a range of deformation-zone lengths from < 3 to > 10 km, and baseline radii of 50 m and 25 m radii for fractures that can be reliably be detected and avoided in the repository. In addition, in response to Swedish repository-design guidelines, transition zones within which no canister can be emplaced, are tentatively defined at thicknesses of both 1 % and 2 % of the length of the deformation zone. In general, a respect distance of 100 m from identified deformation zones appears to be adequate. In addition, no attempt seems to have been made to estimate the effects of reactivation of pre-existing structure on the flow and transport properties of those structures.

Bedrock Geology and Intact Rock Mechanics

The bedrock intrusions in the Simpevarp area date from 1,810 to 1,760 mybp. Three lithologies dominate on the Simpevarp peninsula:

- Fine-grained, inequigranular dioritoids (rocks of the diorite family).
- The Ävrö granite (a granite to quartz monzodiorite), which is generally medium grained and porphyritic.
- Quartz monzodiorite, medium-grained, equigranular to weakly porphyritic.

Subordinate rock types at the local scale include:

- Granite, fine- to medium-grained
- Pegmatite (very coarse-grained)
- Mafic rocks; i.e. fine-grained diorite to gabbro

- Granite, medium- to coarse-grained
- Diorite to gabbro, medium-grained

Contacts between the different lithologies are noted as generally being gradational. In addition, it is noted that the Ävrö granite characteristically contains abundant inclusions or enclaves of different rock types. Thus, lithologic heterogeneity among numerous crystalline rock types appears to be characteristic at Simpevarp.

For purposes of the Simpevarp PSE (SKB, 2005b), the site-scale modeling domain is simplified to contain only three rock bodies: a) a domain consisting predominately of the Ävrö granite (75−84 %); b) an area consisting predominately of fine-grained dioritoid (90.6 to 94.2 %); and c) an area of mixed quartz monzodiorite and Ävrö. Intact mechanical properties are further generalized, in that the mechanical properties of the mixed monzodiorite-Ävrö body are assumed to be the same as those for the Ävrö granite alone. From the literature, it appears that four general sets of possible criteria are used to combine and lump lithologies:

- matrix criteria focused on rock mechanics, related to excavation stability during and after the construction, operation, and post-closure phases
- rock mass criteria, focused on lithologically correlated fracture frequency/orientation/character, related to excavation stability during and after the construction, operation, and post-closure phases
- matrix criteria related to long-term radionuclide migration (e.g., critical mineralogy, effective porosity, matrix diffusion rates, sorption capacities)
- lithologically correlated fracture frequency/orientation/character criteria related to long-term radionuclide migration

The main decision as to whether or not to lump lithologic types for purposes of defining domains for later numerical modeling seem to be made largely on the basis of the professional judgment of the participating geologists.

2.8.1.2 General Geology – Forsmark

The Forsmark candidate site lies, as does the Simpevarp area, on the eastern coast of Sweden, adjacent to the Baltic Sea. Although the Forsmark site is approximately 375 km north of Simpevarp, the same broad geologic history applies to both areas. The main distinction between the two areas, from the perspective of geologic and structural history, is that the intrusives at Forsmark are significantly older than those at Simpevarp (e.g., analyzed crystallization ages at Forsmark range from 1,886 to 1,851 mybp, compared to 1,810 to 1,760 mybp at Simpevarp).

Thus, the intrusives at Forsmark are broadly syn-tectonic; and were intruded roughly at the peak of deformation of the major Svecokarelian orogeny (1.960−1,750 mybp). In contrast, the intrusions at Simpevarp are post-tectonic. Two practical considerations result from this difference. First, the intrusions at Forsmark have undergone penetrative deformation and metamorphism, and should be thought of as meta-igneous rocks. Secondly, both local-scale and regional-scale deformation play a major role at the Forsmark site, including widespread distribution of anastomosing ductile and brittle deformation zones. In fact, as noted in the previous section, the candidate volume of meta-granite at the Forsmark site occurs as a tectonic lens, which is approximately 25 km in length and 4 km in maximum width (at surface). Both metamorphic grade and deformation are variable within the candidate volume. In general, however, linear deformation structures are dominant over planar structures in the candidate volume, while planar structures appear to be more dominant in the surrounding rocks. The penetrative deformation is believed to have occurred under high-grade metamorphic conditions (amphibolite facies) (SKB, 2005c). For purposes of the Forsmark PSE, the lithologic distribution is simplified to include only (meta) granite to granodiorite and (meta) tonalite (quartz diorite).

2.8.2 Status of Site Selection

At present, site-specific studies are being carried out at both the Forsmark (Östhammar municipality) and Simpevarp/Laxemar (Oskarshamn municipality) sites. It is interesting to note that, in Sweden as in Finland, public acceptance of nuclear programs is apparently influenced by a relatively successful history of past governmental-public and/or utility-public interactions. In the case of the Forsmark area, there is an existing nuclear plant nearby. In the case of the Oskarshamn area, the Äspö Underground Research Laboratory (URL) lies within the municipality, and a fuel interim-storage facility (Clad) is already operative.

2.8.2.1 Site Selection

The planning and status of the Swedish site-selection program, through 2002, is well documented in Milnes (2002), including site-specific references. In summary:

- The Swedish site-selection program began in the mid 1970's, with national-scale and regional studies extending until ~2000. The initiation of the work was stimulated by the 1977 'Stipulation Law', linking continued development of nuclear power in Sweden to the demonstration of the capability for safe waste disposal. This effort culminated in a 1984 national referendum regarding the combined issues of nuclear power and nuclear-waste disposal.
- Phase 2 of the country-wide and regional studies (1985-1992) was based on the broad concept that possible areas of interest could be defined on the basis of geologic provinces; e.g., areas in which the basement rocks were either buried by too thick a sedimentary cover, or had been involved in active post-Precambrian (Caledonide) deformation, were excluded. Thus, by the end of this phase, focus had centered on the Baltic Shield, comprised of crystalline rocks, including both plutonic and high-grade metamorphic rocks.
- Six study areas within the Baltic Shield were identified and partly characterized during this stage of the effort. During this time interval, experimental studies, not linked to a specific site, were also begun and conducted at both the Stripa mine and the Äspö URL.
- During Phase 3 of the national and regional studies, site-selection criteria (both technical and non-technical) were developed by SKB and ultimately approved by the government (1994). A series of feasibility studies at the county (i.e. prefecture) scale (Länsstudier) was conducted in 1997 and 1998. The main focus of these studies was to compile the available information, on as broad a basis as possible. The effort included formal publication of work that had only been available previously as raw data.
- Because of their focus on waste disposal, the county-wide studies considered five specific areas, including:

- Up-to-date compilation of geological map coverages, aerial geophysics, and ongoing work.
- Definition of areas of high ore potential, to be avoided, due to possible conflicts of interest and future human intrusion.
- Structural maps, showing the (estimated) extents of both brittle and ductile deformation. These areas were avoided because of their presumed adverse underground characteristics.
- A synthesis of the available hydrologic data from wells penetrating bedrock. This work included maps showing variations in bedrock permeability.
- Compilation of available data on thicknesses of Quaternary deposits each county and chemistry of bedrock groundwaters.

There is some overlap of country-scale, regional-scale, and county-scale studies with municipality scale feasibility studies. The municipality-scale studies (Förstudier), conducted between 1993 and 2000, culminated with studies of 8 study areas. In each case, the studies were to be carried out only if there existed a joint interest from both the municipality and SKB to study the issue further (Milnes, 2002). Further, the studies would need to be carried out with close interaction from the local population and other interested parties.

Local referenda at two of the municipalities resulted in decisions not to allow further work (SKB, 2001). SKB evaluated the available information from the remaining six municipalities, and in 2000, recommended three for actual site investigation. After governmental review, four municipalities were still (as of 2000) under consideration (listed in chronological order of original work): Östhammar, Oskarshamm, Tierp, and Älvkarleby.

Note that, as of 2000, four Swedish municipalities had agreed to be the focus for site-characterization work, but that no intrusive site characterization had been carried out. SKB did, however, publish a preliminary evaluation, identifying the areas within each municipality considered most favorable for further investigation. It is explicitly noted that this evaluation used the results of both geotechnical and environmental/societal studies to develop a provisional definition of candidate areas within each municipality (Milnes, 2002).

Documentation of the timing and process of final down-selection to the Forsmark and Simpevarp potential repository site areas has not yet been located. Only these two areas are considered in the following section.

2.8.2.2 Site Characterization

Active site-characterization studies are ongoing at both the Simpevarp and Forsmark sites, and extensive documentation of the individual site-descriptive models (SDM) is available (SKB, 2005c; 2005d). The SDM documentation, which is very detailed, combines and interrelates raw data, conceptual models, and data summaries that are appropriate for Preliminary Safety Evaluations (PSE's).

The work at both sites includes limited numbers of deep boreholes (all normally inclined and cored; 5 deep holes at Simpevarp, 8 at Forsmark), detailed surface mapping of lithologies and fractures, combined with topographic and airborne physics studies aimed at identification of lineaments corresponding to deformation zones.

At both sites, numerical modeling of the bedrock uses an approach combining intact rock properties (lithology, mechanical and thermal properties), deterministic representation of known/probable major deformation and/or high-conductivity zones, and stochastic representation of fracturing and related flow within the rock mass between identified deformation zones, by means of Discrete-Fracture Network (DFN) models.

At Simpevarp, three alternative DFN models have been generated, depending on assumptions regarding the number of near-vertical fracture sets (2 models) and linkage with observed sub-horizontal fracturing in boreholes (1 model). The multiple models are indicative of remaining conceptual uncertainty. It is explicitly noted that there is concern regarding the fracturing intensity for fractures ranging from 10 to 1000 m scale. Results to date indicate that frequencies of sub-horizontal fractures, based on outcrop data, appear to be too high, relative to estimates from boreholes, by a factor of about 2. This internal inconsistency was eliminated in the 'hydro-DFN model', which combined outcrop and borehole data.

For the Simpevarp site, the local-scale structural model (21 km^2) contains 188 deformation zones, which are modeled deterministically (SKB, 2005b). Of these, 22 are considered to be of high confidence. The mapped deformation zones include both ductile and brittle zones, and are not generally discussed in terms of discrete fracture sets.

At the Forsmark site, the deterministic deformation zones are discussed in terms of four distinct sets:

- Vertical and steeply dipping zones striking WNW-NW. These are interpreted as regional structures, with complex combinations of ductile and brittle deformation. These composite first-order structures define the margins of the Forsmark candidate volume, are dominated by sealed fractures, and contain mylonites, cataclastic rocks, and cohesive crush breccias.
- Vertical and steeply dipping zones that strike NS. These zones formed in the brittle regime, and are dominated by sealed fractures. The structures, which are apparently widely spaced, are assigned low confidence, and are not included in most of the site-scale models.
- Vertical and steeply dipping zones with NE strike. These brittle-deformation zones are generally more local in character, transect the candidate volume, and are dominated by sealed fractures and development of cohesive crush breccias.
- Brittle-deformation zones dipping gently to the SE and S. This set has the highest frequency of open fractures/joints and non-cohesive or incoherent fault breccias.

There does appear to be a qualitative difference between the levels of site characterization at Simpevarp and Forsmark, due to the fact that the Äspö URL lies in the northern part of the Oskarshamn region, 1.5 km north of the northern side of the Simpevarp peninsula and is developed largely in the Ävrö granite, which is the same material that is dominant at Simpevarp.

2.8.3 Flow and Transport Data

Two general types of data are included in this section. Data considered to be readily available are taken directly from the PSEs and SDMs prepared for the Simpevarp and Forsmark areas. Summary data from these sources represent either first-generation (SDM) or second-generation (PSE) generalizations of the available experimental data.

2.8.3.1 Parameter Values

Forsmark

The conceptual model for the Forsmark site implies that only fractures and fracture zones should conduct water, although diffusion is allowed in the matrix (SKB, 2005a). In the model, the conductive zones are divided between Hydraulic Conductor Domains (HCD's), which are assumed to coincide with the deformation zones in the geological model, and the Hydraulic Rock Domains (HRD's) representing the rock mass between the HCD's. HCD's are modeled deterministically while the HRD's are modeled using a Discrete Fracture Network (DFN), with assigned hydrologic properties.

There are 44 deformation zones in the Forsmark flow model of which 27 have been tested hydraulically. The interpretation in the Forsmark PSE is that with regards to transmissivity, a) the transmissivities of steeply dipping structures and more shallowly-dipping structures are distinct, with the more steeply dipping structures, on average, being less transmissive; and b) there is clear depth dependency of transmissivity for both types of structures. The database used to compile the transmissivity-depth trends at Forsmark are based on field testing (SKB, 2005c) and no distinction is made among brittle, ductile, or composite deformation zones. In the deterministic modeling of flow properties in the HCD's, uncertainty has been addressed, by consideration of three alternative models for the distribution of HCDs, rather than by property variation within a given model.

Hydraulic properties within the Forsmark rock mass (i.e., between HCD's) were modeled independently by two groups, using the hydro-DFN network. For the candidate (repository) volume at Forsmark, the available data indicated essentially no inflow. Nonetheless several specific uncertainties are noted pertaining to the DFN model. These include uncertainties in:

- Division of the rock mass into different volumes (based on deterministic positioning of deformation zones)
- Connectivity of individual structures within the DFN
- Distribution of transmissivities within the fractures included in the DFN
- The possibility of hydraulic anisotropy within the DFN
- Spatial variability of the hydraulic properties of the fractures

There is considerable discussion in the Forsmark PSE regarding the degree of correlation in the DFN between estimated fracture sizes and assigned transmissivities. However, it appears that there are not enough available field data to discriminate among the several different approaches considered.

Simpevarp

As at Forsmark, the conceptual model for flow used in the PSE for Simpevarp divides the rock mass into deterministic HCD's and stochastic HRD's (SKB, 2005b). High-confidence borehole intersections have been identified for 13 of the defined deformation zones. The estimated range in interpreted transmissivities is 1×10^{-8} to 3.6×10^{-4} m^2/s. Where data do not exist, transmissivities for the HCD's were assigned the mean value as obtained from the Äspö URL (1.3×10^{-5} m^2/s).

As at Forsmark, the modeling in the PSE for Simpevarp uses a DFN approach for flow modeling of the HRD's. Again, the HRD's were modeled independently by two modeling groups. Similar uncertainties are considered in the two reports.

2.8.3.2 Data Collected at Äspö

The Äspö URL has been a site of significant *in situ* experimentation and characterization, with most of the research focusing on near-field processes that can be conducted and measured from within the URL. The Swedish program has done an impressive amount of work at Äspö regarding facility monitoring (Almén and Stenberg, 2005) and both flow and transport experimentation (e.g. Bossart et al., 2001; Hauser et al., 2003; Hodgkinson and Black, 2005; Munier, 1995; Windberg et al., 2000). With the exception of the large-scale characterization studies discussed above, the balance of the Äspö will not be addressed here due to the near-field nature of the work. As the Japan site selection process moves from the PIA phase to the DIA phase, the research from the Äspö URL will become more applicable.

2.8.3.3 Interpreted Importance of Active Tectonics

The potential Swedish sites at Forsmark and Simpevarp lie in heavily glaciated parts of the Baltic Shield. SKB has prepared a detailed report on the effects of deglaciation on the crustal stress field and the implications for post-glacial faulting at the national scale (Lund, 2005). This report notes the occurrence of large faults in northern Scandinavia that are hundreds of kilometers long and have offsets of more than 10m. These are generally accepted to be the results of major earthquakes triggered by the retreating ice sheet about 9,000 years ago.

Potential impacts of such major glacial-related faulting are explicitly included in a second SKB report (Bäckblom and Munier, 2002) that considers the potential impacts of earthquakes on a Swedish repository; though it is noted that the most major earthquakes historically occurred in northern Sweden. The seismic respect distances on either side of major structures within a hard rock repository are estimated in this report.

Bäckblom and Munier (2002) also describe the generally accepted description of fault zones as a core zone that is based on fracture frequency parameters, and a transition zone that is based on degrees of deformation. For their purposes, they describe four categories of transition zones and two categories of core zones. They make no requirement for the zones to coincide, although the general discussion is in terms of re-activation of pre-existing structures, with the resulting implicit assumption being that the zonation in the original and re-activated structures will be broadly parallel.

2.8.3.4 Remaining Uncertainties

One of the impressive aspects of the Swedish program is, in addition to having their Research, Development, and Demonstration (RD&D) plans formally reviewed by the government, they publish them, making them readily available to the public. The most recently published RD&D plan is contained in SKB (2004b). This information is summarized below, and is used here to draw conclusions regarding what issues SKB believes to be important with regards to future investigations. These are broken into three specific areas, groundwater flow, reactivation, and fracturing.

Groundwater Flow

- New process knowledge has been gained from large-scale (super-regional) modeling, indicating that local flow patterns (flow cells) are strongly influenced by the ratio between local and regional gradients, and can dominate flow down to repository depths. These studies also show that the presence of saline groundwater at depth may serve as a floor for groundwater flow, effectively increasing the effects of local flow cells.
- Work is planned to better understand the compositional evolution of groundwaters, both past and into the future.
- The ability will be added to model the open repository directly through assignment of boundary conditions.
- A specific study will be done on ways to model density-driven and two-phase flow in discrete-fracture networks.
- No mention is made regarding any need for additional drilling and/or hydraulic test interpretation at either of the two candidate sites.
- There is no mention of time-dependent hydrologic properties (e.g. possible changes in the hydraulic properties of deformation zones, in response to future seismic re-activation).

Reactivation – Movements Along Existing Fractures

- The general belief is that earlier estimates of induced fracture/fault movements were probably conservative, in that they assumed frictionless fracture/fault surfaces.
- There is concern from the authorities that SKB needs to better support the assumption that new fracturing due to future glaciation will not affect a tectonic lens such as that found at Forsmark. There is also concern that SKB include the possibility of future fault movements along new lines in their numerical calculations.
- A compilation of earthquake-induced damage to underground structures was produced.
- The general relationship between length of a fracture and possible movement along that fracture will be reexamined.
- Possible fracture-fracture interactions will be examined.
- The mechanism analysis for post-glacial fault movements will be examined.
- The possibility that the repository, viewed as a unit, may act as a single plane of weakness will be examined.
- There is no identified need for increased understanding of the relationship between the number of re-activations that a given deformation feature has experienced in the past and the hydrologic properties of that zone, nor is there any documented concern regarding the possible impacts of such generation on the hydrologic properties of the affected deformation zone(s).

Fracturing

- Coalescence of individual fractures (on a 100-m scale) due to reactivation. This could examine the limitation of large displacements by energy consumption in fracture propagation.
- The pillar-stability experiments ("Aspe experiment") at Äspö will be conducted and interpreted.

2.8.3.5 Issues Remaining to be Answered

It appears that the remaining issues have largely to do with far-field flow and transport. These issues have been discussed in previous sections.

2.8.4 Comparison to NUMO's Site Selection Process

The success of the Swedish site-selection process to date has been linked at least locally, to a history of successful interactions between the local population and local nuclear facilities, including both the utility companies operating these facilities and the governmental authorities responsible for both permitting their construction and monitoring their operations. The siting of potential repositories at the same location to existing nuclear facilities has several impacts:

- If the public acceptance of the existing nuclear facility is high, gaining local approval for site-selection and site-characterization activities may be easier.
- Assuming that at least some characterization work was required for approval and construction of any pre-existing nuclear facilities, this information, if readily available, can provide a significant source of data in site characterization information.

Effective co-location of nuclear facilities and a repository greatly reduces issues regarding waste/fuel transportation from facility (or facilities) to repository.

2.8.4.1 Interaction with the Public

As described above, the Swedish program went through a well-thought out screening process, from national- and regional-scale to local-scale, and ultimately site-scale activities. Numerous local communities were contacted at early stages of this process, ending up, as summarized in SKB (2001), with local feasibility studies being conducted at six possible sites: Östhammar (Forsmark), Nyköping, Oskarshamm (Simpevarp), Tierp, Hultsfred, and Ävkarleby. Local referenda were held regarding whether or not to allow further study. Two of the communities involved decided, by process of such referenda, not to allow additional work.

2.8.4.2 Distribution of Technical and Programmatic Information

SKB has placed considerable time and effort into the distribution of technical and programmatic information to the public. Their main venue of interaction is their web page (SKB, 2006; SKB Website: http://www.skb.se/default____8563.aspx), which is well organized and contains links to press releases, publications, and a comprehensive links page with links to Swedish governmental authorities, domestic nuclear power programs, and international organizations that address nuclear waste issues. The one limitation to the available information might be the lack of summary material that provides a high-level chronology of the events and progress of the repository program. In addition to the website, SKB conducts tours of its research and testing facilities. In 2005, over 20,000 people visited these facilities, with the largest visitor category being school children. The local population has shown interest in this program with approximately 25 % of the total visits being from people who either live or work in the municipalities of Oskarshamn or Osthammar.

2.9 Switzerland

In 1972, the Swiss federal government and the operators of their five nuclear reactors, which generate 3.2 GW and are expected to produce a total of ~3,000 MT of spent fuel or ~500 m^3 of vitrified high-level radioactive waste, founded NAGRA – the National Company for the Storage of Radioactive Waste (Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle). In 1978, NAGRA started selecting potential sites for low- and intermediate-level radioactive waste. By 1981, the list was trimmed from 100 to 20 locations where further research might be conducted. Evaluation of these yielded three preferred locations: Bois de Glaive (anhydrite), Oberbauenstock (marl), and Piz Pian Grand (gneiss), and at the end of 1983 NAGRA requested permission to conduct further research at these locations. On September 30, 1985, a license was issued, but it limited NAGRA to construction only of test drillings and forbade the construction of a shaft or repository. In 1987, NAGRA added Wellenberg (marl) to the list of study sites because of its prime geographic location.

2.9.1 General Site Geology

NAGRA has federal licenses to perform fieldwork in two investigation areas: one in crystalline rock and the other in Opalinus Clay. Today, research and development on site selection and site characterization takes place at two corresponding underground laboratories: Grimsel (crystalline rock) in the central Swiss Alps and Mont Terri (Opalinus Clay) in northwestern Switzerland. Opalinus Clay is well-consolidated, fractured shale (claystone) with water content of 4 to 12 % and an extremely low hydraulic conductivity of less than 10^{-12} m/s. Two categories of rock with an exclusive magmatic origin can be distinguished at the Grimsel Test Site (GTS) (Keusen et al., 1989):

1. Granitic rocks: These comprise Central Aare granite and Grimsel granodiorite.
2. Dyke rocks: These comprise up to m-thick dykes of light aplite or dark lamprophyre that penetrate the granite.

This review will focus on the work performed at the GTS that specifically comprises crystalline rock.

2.9.2 Status of Site Characterization

As shown in Figure 4, the GTS is located 1,730 m above sea level under a 450-m-thick overburden of crystalline rock in the central Swiss Alps. The main tunnel system extends for more than a kilometer and was constructed in 1983 and 1984 with a 3.5 m full-face tunnel boring machine with additional drifts constructed with conventional drilling and blasting techniques. The GTS contains a ‘radioprotected zone’ where it is possible to carry out *in-situ* experiments with radionuclides.

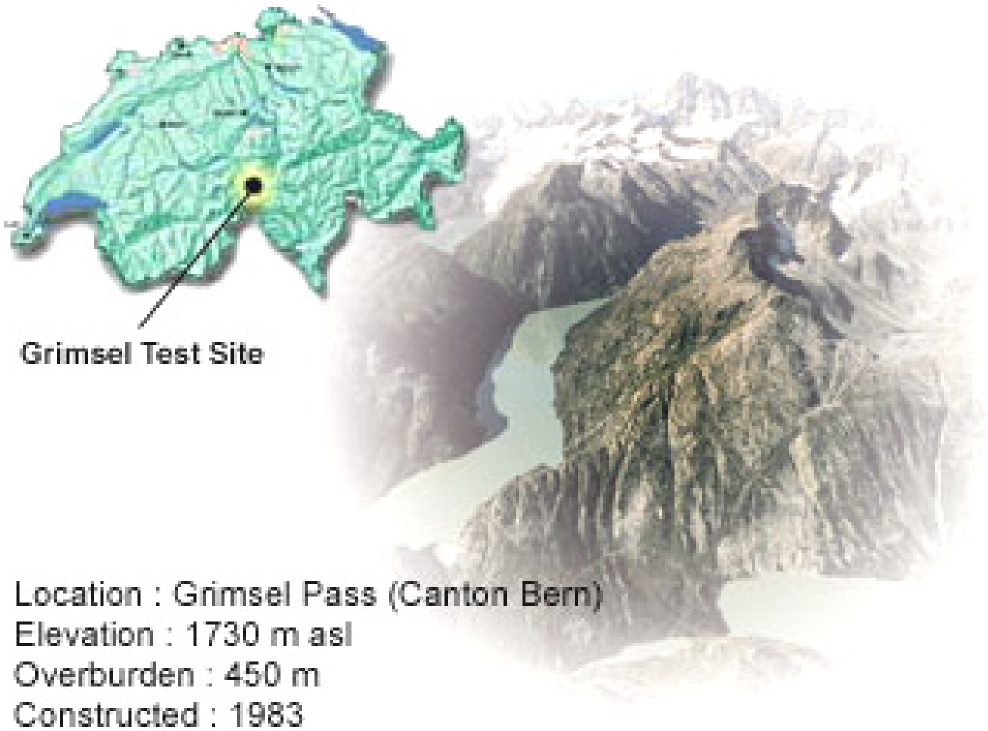

Figure 4 - Location of the Grimsel Test Site.

The geological, hydrogeological, geophysical, and geochemical experiments that have been carried out at the Test Site have four basic objectives (Keusen et al., 1989):

1. Assessing the qualitative and quantitative applicability of foreign research results to the specific geological conditions at Grimsel
2. Carrying out specific experiments that are relevant to the particular aspects of the NAGRA repository concept
3. Building up of know-how at all levels (planning, performance assessment, and interpretation) of underground investigations in different experimental fields
4. Acquiring practical experience in development, testing, and application of suitable measurement techniques and associated instrumentation

Investigations have been ongoing since 1983 with the aim of answering geological, hydrogeological, geophysical, geochemical, and engineering questions. Between 1986 and 1996, the R&D program became increasingly related to performance assessment requirements and individual experiment proposals underwent a systematic ranking and selection procedure. Key areas of interest include: 1) demonstration of sealing technologies; 2) determination of major fracture geometries; 3) characterizing properties of the excavation-disturbed rock zone around the experimental galleries; 4) radionuclide transport; and, 5) emplacement technologies and evaluation of the engineered barrier system. In 1994, a decision was made to curtail basic research and to focus on key areas associated with performance assessment including: 1) application of previous experience to the design of future experiments; 2) demonstrate the feasibility of repository siting and construction; and, 3) validation of previous model predictions.

Using existing databases, experience, and design calculations, new programs are to be initiated in a cost- and time-effective manner. Major recent outputs from the GTS are the variety of approaches used to develop, test, and validate numerical and conceptual models for radionuclide transport and two-phase flow processes through a realistic representation of the engineered barrier system. The project has been broken down into six phases to date.

Phases I and II (1983–1990)

In Phases I and II, a comprehensive investigation program was carried out that included 16 major experiments. In addition to providing detailed information on the geological-hydrological landscape, which is required for planning, performing, and interpreting later tests, Phases I and II improved the understanding of the interaction between modeling exercises, laboratory experiments, and *in-situ* studies. Progress was also made in developing the methodology for performing scientific investigation programs under field conditions. Some of the research projects (e.g., the development of geophysical techniques including underground radar and seismics, the mechanical test of the excavation-damaged zone, the heater test, and rock stress measurements), were successfully completed during Phase II, others continued during Phase III.

Phase III (1990–1993)

Drawing on the experience gained in Phases I and II, the concept for Phase III focused on investigating hydraulic and geochemical/physical transport processes in the rock. The experiments during this phase included the fracture system flow test, the ventilation test, and the migration experiment. In this phase, the role of associated modeling studies became increasingly important.

Models initially used to interpret field observations were used to predict the results of later experiments and such predictions would ultimately be compared with measured data. This aspect of model testing is particularly important because in many cases the manner in which the simulation is carried out can be very subjective and if the answer is known *a priori*, it can be consciously or subconsciously biased. The difference between blind testing of model predictions and testing if a model can simulate particular observations is fundamental, although not always evident in the geohydrology literature.

Phase IV (1994–1996)

More than in the previous project phases, specific safety analysis questions guided of the investigation program for Phase IV. The criteria used as a basis for determining the Phase IV program included the applicability of the results to potential repository sites, an assessment of the chances of success, the suitability of Grimsel as the research site, and possible overlap with other national research programs. Choice of experiments and details of individual research projects were established with input from a range of national partners. Perhaps the most important studies undertaken in Phase IV were the *in-situ* experiments designed to provide a better understanding of transport mechanisms of radionuclides through the geosphere. The *in-situ* experiments culminated in the excavation of the test area and analyses of the distribution of the radionuclides along the test area. The five specific projects carried out during Phase IV were experiments related to:

- Seismic tomography evaluation
- Borehole sealing study
- Study of the excavation disturbed zone
- Two-phase flow experiments and models
- The radionuclide retardation project

Phase V (1996–2004)

In Phase V, the focus was on investigating geological barrier effectiveness, demonstration of disposal concepts, and site characterization investigations. All the projects were also designed to contribute to the further development and assessment of modeling capabilities. There were three main areas of interest:

- Confirmation of fundamental understanding and testing of models of processes identified as significant in integrated performance assessment
- Demonstration and optimization of site characterization technology
- Demonstration of the technology for constructing and operating a deep repository in an efficient and quality-assured manner

Phase VI (2003–2013)

Phase VI began on January 1st, 2003 and represents a major step forward in the research carried out at the GTS. The focus of the new research will be the examination of waste disposal concepts on more repository-relevant timescales and conditions.

2.9.3 Flow and Transport Data

Water flow at the GTS is concentrated almost exclusively within discontinuities (fracture shear zones). The number of water bearing discontinuities noted in the laboratory tunnel covered only 0.013 m^2 per square meter of tunnel wall. Snow melt and rainwater can penetrate into the mountain at primary discontinuities or water can infiltrate into the ground below storage lakes. Shear zones form the primary infiltration pathways, but this does not imply that only these features are wet. Rather, it must be assumed that the whole rock body with all of its joint systems is water bearing; however, many joints appear to be dry because they are closed or healed and their permeability is so low that the wetness is hardly detectable. Average exfiltration from the GTS is only 1.54 L/min (Keusen et al., 1989).

2.9.3.1 Parameter Values

Several of the detailed field experiments were focused on characterizing and modeling a section of shear zone. NAGRA's investigations revealed that the studied shear zone is a reactivated mylonite in a weakly foliated granodiorite. The rock is brittle and heavily brecciated up to 30 cm away (Missana and Geckeis, 2004). Within the shear zone, water flow is concentrated in up to six channels, each 0.1 to 4 mm wide, which are situated in mylonite (porosity 0.1 to 0.4 percent) (Missana and Geckeis, 2004). Characteristics of the predominant granites include a density of 2,660±24 kg/m^3, porosity of 0.1 to 1.0 percent, thermal conductivity or 3.34±0.35 W/m-K, and a range of hydraulic conductivities between 3.5×10^{-12} and 5×10^{-17} m/s (Keusen et al., 1989). The test site groundwater is a Na^+/Ca^{2+}–HCO^{3-}–$SO4^{2-}$ type with a pH of 9.6 and Eh below −300 mV. The electrical conductivity was 103 μS/cm and the ionic strength was 1.2×10^{-3} M (Kurosawa et al., 2006).

2.9.3.2 Data Collected

In many cases, research and development programs are effectively developed 'from the ground up' with proposals from experimentalists providing the primary input for structuring the program. To work 'from the top down', a national waste management strategy is transformed into 5- to 10-year work programs by specifying the input required to meet the identified milestones. Integrated performance assessments are a particularly valuable tool for identifying key uncertainties or database gaps and thus serve as a focus for research and development programs. As repository siting and construction approach, the research and development wish list is extended to include practical information and technological requirements for waste internment.

The list of priority research and development targets derived for the NAGRA program was reduced to those for which the GTS is inherently suitable including experiments related to:

- Scale effects (hydrogeology, geochemistry)
- Dispersion in fracture networks
- Characterization of the excavation-disturbed zone (disturbed rock zone)
- Channeling (characterization)
- Determining the layout zones for repositories
- Measurement and monitoring (methods, reliability, perturbations, data handling)
- Evaluation of reliability of hydrogeological models
- Hydrological/geochemical alterations during repository operations
- Validation of processes (sorption, colloid transport, matrix diffusion, etc.)
- Sealing demonstration (boreholes and tunnels)
- Geochemical perturbations from cement and concrete (high pH plume)

2.9.3.3 Data Collection Methods

Because host rock acts as an important barrier to the transport of contaminants from the repository, it is important to characterize how effectively this barrier performs (Alexander et al., 1996a). Perhaps of most international significance are the Radionuclide Retardation Project (RRP) of Phase IV and the Colloid and Radionuclide Retardation (CRR) experiments of Phase V. Both the RRP and the CRR welcomed international collaboration and the data were freely shared so that each international participant could independently develop numerical models of the experiments. The goal was to have a suite of calibrated and validated flow and transport models, each of which was to be evaluated based on its ability to accurately model the system (Smith et al., 2001).

Radionuclides are commonly used to investigate contaminant migration in groundwater because they can be detected at very low concentrations using a range of analytical techniques. In addition, by selecting short-lived isotopes, no permanent change is made to the system. Radiotracers were chosen based on their importance for repository safety assessment. In addition, for some radionuclides, little is known about their behavior in the geosphere and thus these were also selected (although longer-lived isotopes were selected for these to ensure that they did not decay away before the end of the experiment). The goals of these experiments were to determine, *in-situ*, how flow through and interaction with the granite slows down radionuclide transport. Important mechanisms for repository performance assessment are sorption of radionuclides on fracture walls, diffusion of radionuclides into the pore spaces of the rock matrix, and potential enhanced transport due to sorption onto mobile colloids.

Additional goals of the RRP experiments include methodology development for site characterization, improved understanding of site hydrology and geochemistry in fractured rock, and detailed characterization of a single water-conducting feature. Perhaps most importantly, several conceptual models of radionuclide transport in this system were developed and calibrated. The emphasis of this project was on assessment of the predictive capabilities of transport models (as opposed to model fitting). The modeling exercises were considered successful because relevant processes were understood and represented in the models, no relevant processes were excluded, and confidence was gained that with appropriate considerations of differences in conditions, laboratory data can be applied to field-scale experiments and performance assessment calculations. However, the modeled interpretations of the experiments were not without limitations. For example, it is unclear that results relevant to the time and spatial scale of the experiments are applicable to the scale required for performance assessment. Also, models appeared to be insensitive to the finer details of the system including the effects of channeling, multiple flowpaths, or unlimited matrix diffusion. Overall, the RRP experiments demonstrated that the methodology used to model solute transport in fractured crystalline rock is applicable and effective. Specific successes included:

- Geological and hydrological characterization of water-conducting features
- Simplification of this characterization for modeling purposes
- Adaptation of laboratory data to field conditions
- Successful numerical simulation of the governing equations for solute transport in dual-porosity media

The CRR experiments were undertaken to assess the potential for colloids produced from degradation of the bentonite barrier to act as a mobile third phase and hence facilitate the transport of radionuclides. Thus, the question was whether colloids would interfere with the sorption and diffusion processes that would otherwise retard radionuclides. Actinide radionuclide cocktails, both with and without 20 mg/L of exogenous bentonite colloids, were injected into one pole of the dipole test shear zone. Output solutions from the other dipole were measured for radionuclides and colloid concentrations. In excess of 80 percent of injected bentonite colloids passed through the flow field without retardation or filtration of larger colloids. Further results indicate that tri- and tetravalent actinides form radio-colloids in Grimsel groundwater even in the absence of exogenous colloids, retardation of Am and Pu were greatly reduced in the presence of bentonite colloids, and a small fraction of Cs was transported as colloids.

2.9.3.4 Interpreted Importance of Active Tectonics

Neither the GTS nor Mont Terri are tectonically active, thus there has been essentially no seismic research or investigations into the role active tectonics may play in the hydrogeology at the site.

2.9.3.5 Remaining Uncertainties

Grimsel Phase VI formally began on January 1st, 2003 and represents a major step forward in the research carried out at the GTS. The focus of the new research will be on more repository-relevant timescales and conditions as well as an extensive study of waste disposal concepts.

Three Phase V projects (the Full-scale High Level Waste Engineered Barriers Experiment, the Gas Migration in EBS and Geosphere Experiment, and the Hyperalkaline Plume in Fractured Rock Experiment) have been officially extended into 2005. This allows a greater volume of high quality data to be collected from these projects where long term monitoring is a fundamental part of the investigation. Projects include:

- Development and optimization of the technology for transporting, emplacing, quality-assuring, monitoring, and retrieving of radioactive waste.
- Extending past studies of processes in the geosphere (mainly associated with radionuclide mobility) to more closely represent the physical scales (at least 10s of meters) and boundary conditions (e.g., low water velocities) relevant to repository environments. This requires multi-decade-long tests, more than an order of magnitude longer than has been the case in any rock laboratory anywhere in the world to date.
- Monitoring and extending the knowledge and experience available from the present generation of radioactive waste experts by training the next generation who will actually build repositories.

Current active projects include experiments designed to study:

- Pore Space Geometry
- Colloid Formation and Migration
- Long Term Diffusion
- Long Term Cement Studies

2.9.4 New Technologies Developed During Assessment Process

Perhaps more important than the development of new technologies was building up the knowledge to carry out difficult and expensive underground experiments. Problems included figuring out the logistics for moving equipment underground and working in confined spaces subject to relatively low temperatures, high humidity, and conventional mining constraints. All experiments required some level of practical problem solving that often involved considerable lateral thinking. A good example is the range of work undertaken to determine the rate of water inflow into the GTS and specific locations.

The ventilation test sought to measure water inflow into isolated tunnel segments including both flowing water and water lost to evaporation. The project was initiated by locating fracture zones with high suspected evaporation rates. These could often be identified by the characteristic fluorescence of uranium-coating materials deposited as inflowing water evaporated. For such cases, a miniature ‘ventilation rig’ was developed to measure low, localized flow rates without having to sample over large-scale isolated tunnel sections. In areas of the tunnel where flowing water was observed, various means (including the use of home-made flow meters) were used to isolate and measure flow rates. Many other technologies, too numerous to name, were adapted for specific use in the underground environment of the GTS, applied in a new geological setting, or calibrated and validated to unique site conditions. Fluid logging techniques are an obvious example. These techniques were altered to not only enable quantification of transmissive zones, but to measure ambient flow rates as well. Fluid logging is when fluid with different characteristics from the natural groundwater is used when drilling/developing a borehole. When this drilling fluid is pumped back and analyzed, it can yield information about background groundwater flow.

Apart from the practical aspects of carrying out experiments underground, significant experience has been gained related to planning and interpretation of experimental studies. This allowed future experimental investigations to be organized such that the cost/benefit ratio is optimized. Of particular importance here was the increased integration of modeling and experimental groups. The first steps, which involve developing and understanding complex systems, translating this into quantitative models, and checking the models against site data, are well illustrated by the various studies performed to predict flow and transport at the GTS.

The experienced teams who lead NAGRA programs have, over the years, built up extensive, internationally recognized know-how. Nineteen partner organizations from France, Germany, Japan, Spain, Sweden, Switzerland, Taiwan, the Czech Republic, and the USA, as well as numerous universities, institutes, and companies from Switzerland and abroad, are involved in activities at the GTS. In addition, the European Union and the Swiss Federal Office of Education and Science provide financial support to some projects.

2.9.5 Issues Remaining to be Answered

Alexander et al. (1996b) note that, "One weakness, which has perhaps only now been acknowledged, is that, while the field experimenters, laboratory experimenters, and transport modelers were in it together from the very beginning, the performance assessors were remarkable only by their absence. This would probably be the single greatest improvement possible to ensure the production of PA relevant data from any field tracer experiment – and the eventual inclusion of such data in a repository PA."

2.9.6 Comparison to NUMO's Site-Selection Process

2.9.6.1 General Characteristics

According to Swiss law, final radioactive waste disposal facilities must be constructed to ensure long-term passive safety (i.e., no supervision is required after closure). Beyond this, there are three political levels involved in the licensing process: the federal government is responsible for granting all nuclear waste management licenses, the local canton must approve the plans and grant underground land use, and the local community must be involved in the construction process. The federal licensing process has five stages (Lindskog and Andersson, 2002):

- License for preparatory measures
- General license
- Nuclear construction license
- Operating license
- Closure license

The license for preparatory measures is necessary for drilling exploratory boreholes or excavating shafts and galleries for site investigation. The application has to contain detailed information on schedule, location, and scope, and has to outline how various other requirements are taken into account; these include protection of persons, third party property, and other legally protected interests, as well as requirements relating to nature and habitat conservation and planning. The application is made public and objections can be made within a certain period. Before the federal government decision is made, the cantons and municipalities concerned are also consulted. The general license specifies the site, the general layout of the repository, and the nature and amount of radioactive waste to be disposed of in the facility. The application has to include a demonstration of confidence in operational and long-term safety. The federal government makes a decision after hearings with the siting community, the canton, and various experts and institutions. In some cantons, the response of the cantonal government to the hearings has to be voted on by the citizens of that particular canton, although the vote is consultative in nature. The application and the conclusions reached by the various involved parties are published and anyone can file written objections within 90 days. These objections are evaluated together with the application by the federal government. A positive decision has to be ratified by the federal parliament. The general license procedure is likely to take several years.

The federal government will thereafter, without further need for ratification, make the decisions concerning construction, operation, and closure. The construction and operational licenses are expected to take 2–3 years to obtain and only those who can be considered to be affected by the proposed repository can object. The federal government takes the application, all the reports, and the objections into consideration before reaching its decision. Because the closure license is far off in the future, there are presently no legal requirements concerning post-closure monitoring and maintenance. The federal government is assumed to take over the responsibility for the facility after closure.

In addition to the federal licenses, there are a number of local licenses depending on the legislation of the involved canton. In the case of Wellenberg, a mining concession application has to be submitted to the cantonal government and approved in a cantonal referendum. The reason for this is that mining activities are covered by cantonal law. For Wellenberg, this vote is no longer consultative but binding in status. Other permits are needed for railway lines, forest clearing, environmental protection, building permits, planning issues, water protection, highway construction, nature and habitat conservation, and for industrial enterprises. These permits can be appealed all the way up to the Federal Court and can result in considerable delays. Such a process can take from two to eight years.

2.9.7 Interaction with Public

Federal and local governments have held referendums where the public decided the fate of the construction of both exploration drills and repository construction. For example, in June 1995 the people of Nidwalden Canton where the potential site, Wellenberg, is located voted 52:48 % (72 % turnout) *against* a referendum allowing exploratory drills and repository construction. This referendum halted any further exploration of Wellenberg as a low- and intermediate-level disposal site. When NAGRA studied voting behavior, they found that both voters and non-voters cared about the referendum and they informed themselves through magazines (72 %), television (42 %), radio (32 %), conversations with family (29 %), brochures (20 %), or attending information hearings (16 %). Only 4 % did not inform themselves. NAGRA admitted that they underestimated the emotions of the people as well as the effects of negative TV ad campaigns about the project. This tremendous setback to low- and intermediate-level disposal forced the Swiss government to review and revise its disposal concept. Currently, a stepwise approach is sought where research, development, and internment of waste is sequentially phased in and reversibility or retrieval is ensured at any step.

2.9.8 Distribution of Technical and Programmatic Information

Technical and programmatic information is primarily distributed through NAGRA's website found at: www.grimsel.com.

2.10 United States of America

Site characterization activities with regard to hydrology at Yucca Mountain have been conducted for approximately 30 years. These studies have been performed at the regional and site scales. Part of this effort has been directed at understanding and characterizing groundwater flow through the unsaturated zone (UZ) where the repository is to be located. Because there is little chance of placing a repository in the UZ in Japan, Yucca Mountain Project (YMP) research on unsaturated flow processes will not be covered in this report. It should also be noted that selection of Yucca Mountain did not follow a formal progression (i.e., national screening, delineation of preliminary investigation areas, and detailed investigation) process such as that defined by NUMO for Japan. Both regional- and site-scale investigations often occurred concurrently, dictated by scientific need for clarity with regard to specific processes or boundary condition assumptions.

Considering these factors, the description of site characterization at Yucca Mountain in this report will be limited to those topics of greatest current relevance to the high-level radioactive waste repository program in Japan. The hydrology research for Yucca Mountain at the regional scale will be discussed because of its relevance to work that will be performed during the preliminary investigation area stage in Japan. Where appropriate, greater detail will be included with the intent of describing one possible technical path that NUMO might follow.

2.10.1 General Site Geology

The HLW repository at Yucca Mountain is located in southern Nevada, approximately 160 km northwest of Las Vegas. Yucca Mountain is in the Basin and Range physiographic province, which is generally composed of north-south trending mountain ranges separated by alluvial basins created by extensional tectonics ongoing since the early Tertiary period (BSC, 2004d). Beside the mountainous terrain, the key feature of importance for repository investigations is Fortymile Wash, which is a large surface drainage feature to the east of Yucca Mountain that represents the dominant transport pathway for radionuclide transport.

The planned repository and existing test facilities, are situated in Miocene-aged ash flow deposits of the Paintbrush Group with the Cross-Drift tunnel cutting under the crest of Yucca Mountain. Four distinct tuff units have been identified within the Paintbrush Group including Tiva Canyon, Yucca Mountain, Pah Canyon, and Tonopah Spring Tuffs. The surficial rock-type distribution shows a generalized west-east structural cross-section through the Yucca Mountain block that is indicative of lateral lithologic continuity and fault-separated blocks that compose most of the upper several kilometers of rock in the vicinity (BSC, 2004d) . The zoned ash-flow Tonopah Spring Tuff, a high-silica rhyolite, will be the repository host rock with unit thickness ranging from 280−400 m within the zone of interest. Laterally continuous volcanic lithologies—the Calico Hills Formation, Prow Pass Tuff, and Bullfrog Tuff—compose the > 400 m of rock immediately below the Tonopah Spring Tuff. While the repository will be located in the UZ, extensive faulting and any corresponding preferential flow paths are the likely candidates for potential radionuclide transport into the saturated zone (SZ).

2.10.2 Status of Site Selection Process

In late 2004, a total system performance assessment (TSPA) was submitted for regulatory review for purposes of obtaining requisite license authority to continue to the next phase of repository development. The entire set of reports for the TSPA-License Application (LA) (Figure 5) was reviewed for this report. Note that the four primary inputs shown at the left of Figure 5 (hydrogeologic framework model; water-levels; groundwater flow boundary conditions; permeability distribution) generally constitute the preliminary data necessary for regional hydrogeological screening criteria; subsequently more refined versions are required as the site selection process continues (e.g., to the DIA stage).

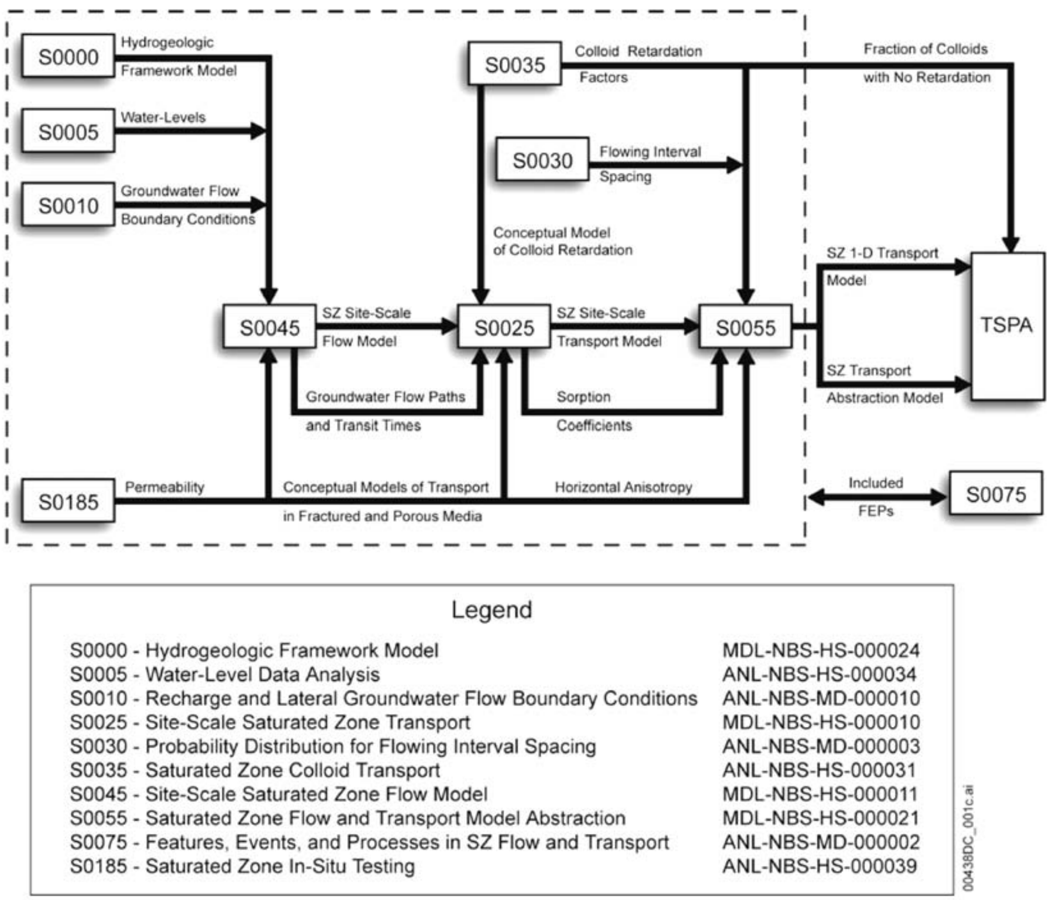

Figure 5 - Information flow paths between the reports compiled to support the TSPA-LA review.

2.10.3 Flow and Transport data

The collection and assessment of hydrologic data associated with Yucca Mountain occurred over several decades, with multiple entities involved (academic researchers, governmental laboratories, governmental agencies). A USGS synopsis of the SZ groundwater system (Luckey et al., 1996) published prior to the focused site characterization of the last ten years offers an equivalent to what is likely available for NUMO national screening and initial PIA assessments. The literature shown in Figure 5 will be summarized to provide a review of the United States' procedure at the equivalent PIA site selection-site characterization stage in NUMO's decision process.

2.10.3.1 Parameter Values

By 1996, the flow system at and around Yucca Mountain had been sufficiently characterized to develop both a regional- and site-scale model. The telescopic development of such an understanding is required in a geological situation as complicated as the Yucca Mountain region, "...because there are no natural hydrologic boundaries in the saturated zone at the site scale [and] the discussion of the site-scale saturated-zone flow system needs to extend beyond the 150-km^2 area generally considered..." (Luckey et al., 1996). Regional flow paths in the upper ~2 km of the crust and Quaternary overburden generally follow the topographic gradient, resulting in north-to-south transport from the high plateaus to the Amargosa Desert. An existing well network, some drilled during studies associated with Nevada Test Site research, was used to produce a potentiometric surface for the Yucca Mountain region in sufficient detail to demarcate three regimes of distinct hydraulic gradients as well as a vertical stratification in vertical hydraulic gradients locally tied to the basement carbonate aquifer through fault-related conduits. The deeper carbonate rocks of Paleozoic age underlying the Tertiary volcanic sequences (> 2 km depth), particularly in the Yucca Mountain area, were believed to be generally hydrologically isolated by a volcanic confining unit at the Tertiary-Paleozoic contact. However, deep faults and associated rock alteration have been identified that suggest hydraulic communication in the past.

While the stratigraphy in any area is locally heterogeneous, a simplified two-aquifer, two-confining unit hydrogeologic model for the volcanic sequence in the Yucca Mountain area had been widely accepted and parameterized by field and laboratory measurements. The aquifers were perceived to be heterogeneous with flow dominated by channelized fracture/fault flow. The confining units were not conceptualized as impermeable, with flow being focused in strain-localized domains rather than through the bulk rock matrix. Table 9 summarizes the regional hydrologic research components for the Yucca Mountain region (Luckey et al., 1996).

Table 9 − Elements pertinent to regional hydrologic research at Yucca Mountain.

Component	Data types	Applications
Potentiometric surface	water level readings (static)	horizontal and vertical gradients flow communication indicators
Potentiometric-level transients	water level readings, monitored over multiple time lengths	fluid pressure dynamics from earthquakes, local pumping, long-term changes in water usage
Hydraulic data aquifer tests flow surveys	single- or multi-borehole pump tests, static and pumped/transient radioactive (or other) tracer concentrations	hydraulic conductivity, transmissivity, storativity, identification of aquifer compartmentalization, determine intervals that produce or accept water
Inflow to volcanic system upgradient inflow recharge infiltration upward flow from basement	water level data, water balance modeling, streamflow measurements	define general input boundary conditions for conceptual and numerical models
Outflow from volcanic system downgradient outflow pumpage downward flow to basement flow into unsaturated zone	water level data, water balance modeling, streamflow measurements, well pump logs	define general output boundary conditions for conceptual and numerical models
Water geochemistry	major ion concentrations, Li, Sr, Br concentrations, pH, eH, temperature, specific conductance, isotopes (C, H, O)	water provenance determination, water flow paths, qualitative and quantitative calibration of flow and transport models, absolute and/or relative age of groundwater, calibrate water-rock interaction modeling
Paleohydrology discharge deposits zeolitization/other diagenetic alterations	water geochemical data	calibrate numerical modeling of flow and transport/water-rock interaction, may be tied to climatic or longer-term changes due to tectonic history

2.10.3.2 Data Collected and Analysis Performed During Regional Assessment

The SZ in the region of Yucca Mountain was divided into two types of flow systems along the flow paths between the repository and the accessible environment: 1) fractured tuffs that underlie the repository and are laterally extensive to the south of Yucca Mountain; and 2) downgradient valley-fill or alluvial deposits within the 18-km performance compliance boundary that is set by the regulatory agency. Hydraulic and tracer tests were completed to characterize the two flow systems. In the case of the fractured tuff, tests were performed at a three-well complex known as the C-wells. The C-wells are located approximately 2 km southeast of the repository footprint. To characterize the saturated alluvium, hydraulic and tracer tests were conducted at the Alluvial Testing Complex (ATC). The ATC is located just outside the southwest corner of the Nevada Test Site, adjacent to the compliance boundary.

Water-level measurements

Water-level data were used to generate a single representative potentiometric surface for the SZ site-scale flow and transport model domain. Water-level measurements were also used for the estimation of aquifer storativities and transmissivities. Water levels were measured in and around the model domain and were collected through collaborative efforts of YMP researchers and the Nye County Early Warning Drilling Program (EWDP). The potentiometric surface represents the top of the SZ and it defines the upper elevation where radionuclides enter the SZ.

The source data associated with the YMP water-level analysis include eight types of information gathered from each borehole:

- Borehole site name/identification (ID)
- Location
- Land-surface altitude
- Water-level altitude
- Data source, reliability of data
- Minimum and maximum water levels (range)
- Open interval monitored with the associated water-level altitude
- Well type

Professional judgment was used to determine whether water levels reflected perched water conditions based on the following criteria: proximity to cold-water springs, proximity to recharge areas, steep or anomalous potentiometric-surface slope, anomalous water-level altitudes, statistical water-level variability, water chemistry, pumping history, and hydrographs (O'Brien, 1988).

The scope of the potentiometric surface analysis includes:

- Compilation of water-level data within the SZ site-scale flow model area through 2003. Included are:
    - Data from the original analysis (USGS, 2001) with end dates from 1952 to 1999
    - Data from the alternative interpretation conducted in 2001 (USGS, 2004) with end dates in 2000 for the Nye County wells
    - Data from Yucca Mountain site wells through 2001 to assess temporal variability of water levels
    - Data from the Nye County wells through 2003 to assess the impact of the new well data
- Removal of duplicate measurements and sites.
- Tabulation of measurement precision, where known.
- Assessment of the general reliability of the data.
- Tabulation of the range in water levels for the use in uncertainty analyses.
- Documentation of the applicable use of water levels (potentiometric-surface development and SZ site-scale flow model calibration).
- Generation of the potentiometric-surface map representative of the early 1990s that is used to provide boundary conditions to the SZ site-scale model (BSC, 2004a).
- Identification of vertical head differences within the SZ site-scale flow model area. These head differences provide additional calibration targets for the model.

- Assessment of water-level uncertainty, discussion of the impacts of the uncertainty on the potentiometric-surface, and comparison of the potentiometric-surface from this analysis with surfaces generated by other analyses.

Recharge estimates

The recharge estimates were derived from three sources (the site-scale UZ model, the regional-scale saturated-zone model, and Fortymile Wash data) which are combined into a single result. Recharge from the site-scale UZ model was taken as the flow through the base of that model (approximately 40 km^2 that encompasses only the footprint of Yucca Mountain). The recharge data from the UZ model included dual-permeability effects and the output from the model includes fracture and matrix flow.

Flow meter surveys in wells

A McCrometer turbine-type flowmeter was used during hydraulic tests conducted at the C-wells complex in June 1995. Subsequently, the primary device used for monitoring discharge was a differential-switched-capacitor vortex flowmeter that measures vortex frequency past a bluff body. The flowmeter signal was recorded at user-specified intervals by monitoring software installed on a personal computer. The software program used a regression equation developed on the basis of the flowmeter calibration to convert the voltage signal from the flowmeter to a discharge rate.

Pump testing

C-Well Complex

Hydraulic testing was conducted at the C-wells complex over a fifteen year period. All tests except the last five provided information on flowing intervals within each well. Measured parameters also included storativity, transmissivity, and hydraulic conductivity. In four of the tests, the C-wells were equipped with packers that could be inflated to isolate selected intervals.

Distant observation wells were typically open holes and data from these wells provided insight into large-scale aquifer properties. One long-term high-discharge pumping test was performed to provide sufficient data for an approximation of anisotropy in the vicinity of Yucca Mountain. The test was conducted at a location just east of the proposed repository block. The test included measurements at more than 20 observation wells (Stuckless and Dudley, 2002).

The results of the pump test indicated long-distance continuity in fracture permeability. Storativity and transmissivity estimates were obtained from observation-well drawdown data by fitting these hydrologic parameters to various analytical solutions of the groundwater flow equation. All hydraulic test data was corrected for barometric pressure and earth tide fluctuations prior to being analyzed. The analytical solutions employed included the unconfined aquifer solution from Neuman (1975); the confined aquifer, single-porosity solution from Theis (1935); the confined-aquifer, dual-porosity solution from Streltsova-Adams (1978); and the leaky-confined aquifer solution from Hantush (1966). With the exception of the Neuman (1975) unconfined-aquifer solution, which assumes both vertical and horizontal flow, these analytical solutions assume radial flow to the pumping well in a homogeneous, isotropic aquifer of constant thickness. The analytical solutions used for each of the test intervals were selected based on the characteristic shapes of the interval drawdown curves and knowledge of interval flow characteristics gained from previous logging and testing.

Alluvial Testing Complex (ATC)

Hydraulic testing at the ATC was conducted over a two-year period from July 2000 to July 2002. Single-well tests included separate tests where each of the four intervals completed in the alluvium were isolated (by inflatable packers) and pumped. The well was also pumped as a single interval. These tests provided insights into the relative transmissivities and general characteristics of the four screened intervals completed in the alluvium at this location.

The single-well hydraulic tests all indicated that the alluvium in the immediate vicinity of the pumping well behaves as an unconfined porous medium. Although the transmissivity estimates from these tests were considered biased to the low end because of large well losses, there was good agreement between the hydraulic conductivity estimates in three of the four isolated screened intervals as well as in the test involving all four combined intervals (correcting for the fully penetrating solution assumption). The hydraulic test results suggest that the hydraulic conductivity of the alluvium does not vary significantly with depth.

Mineralogical studies

Extensive mineralogical sampling and analysis was used to develop SiO_2-Al_2O_3 relationships to differentiate the various volcanic units in the vicinity of Yucca Mountain (BSC, 2004d). Geochemical rock type was found to strongly correlate with other important physical, fluid geochemical, and hydrologic properties of the respective lithologies. Thus, mineralogical assays may play a vital role in quickly characterizing a region when only a few time- and money-consuming laboratory measurements on physical and hydraulic properties are available.

Diagenetic geochemical processes can also be monitored for important hydrologic information. At Yucca Mountain and the surrounding area, a common depth-dependent transition from vitric to zeolitized tuffs has been observed. In particular, the areal and depth distribution of zeolitization has been used to infer the extent of perched water conditions through time and to estimate the highest static water level ever reached under Yucca Mountain (BSC, 2004d).

Hydrochemistry

The hydrochemistry was analyzed to characterize groundwater recharge rates, flow directions and velocities, and mixing proportions of water from different source areas based on groundwater geochemical and isotopic data (BSC, 2004a). In particular, a number of geochemical parameters were calculated including: charge balance error, ionic strength, dissolved inorganic carbon (DIC), the logarithm of dissolved carbon-dioxide partial pressure (log P_{CO_2}), and the saturation indices of various minerals. The charge-balance errors are helpful in evaluating the reliability of hydrochemical analyses. The calculated DIC concentrations are used for evaluating the extent of calcite dissolution during recharge as water moves through the SZ and in mixing models involving ^{14}C. The saturation indices are used to help constrain the possible reactions in inverse mixing and water/rock interaction models (BSC, 2004a). Over 200 groundwater samples were collected for the hydrochemical data set.

For the purpose of calculating mineral saturation indices, when field temperature measurements are unavailable, the temperature of groundwater samples was approximated either from published maps of water table temperatures at Yucca Mountain or assumed to be 25°C (Fridrich et al., 1994).

Groundwater age dating

Chemical and isotopic data were used to characterize groundwater flow speed and to estimate the age of the groundwater in the region. The analysis of water chemistry data and isotopic data took into account all variables that have an affect on the groundwater chemistry, including precipitation, evaporation, mixing, and water-rock interactions (BSC, 2004a).

Where spatial differences in their concentrations existed, hydrogen and oxygen isotopes were used to trace groundwater movement. In addition to the hydrogen and oxygen isotopes, four other isotopes were used to characterize the age of groundwater in the region: carbon, sulfur, uranium, and strontium (BSC, 2004a).

Field-scale tracer testing

C-Wells complex

Tracer testing was conducted at the C-wells complex over a four-year period from 1996 to 1999. Estimates of transport parameters were obtained from the tests by fitting the tracer breakthrough curves using semi-analytical dual-porosity transport models. A key objective of the tracer testing was to determine if a dual-porosity conceptualization is valid in the saturated volcanic tuffs or if the tuffs behave as a single-porosity system (with no secondary porosity into which solutes can diffuse). Distinguishing between these two types of conceptual models has important implications for radionuclide transport because a dual porosity system will show increased tailing in the breakthrough curve due to matrix diffusion or chemical sorption. This effectively slows the transport of radionuclides through the system.

Field methodology

Tracer tests were conducted in both a high transmissivity interval (the lower Bullfrog) and a low transmissivity interval (the Prow Pass) at the C-wells to determine if transport behavior and transport parameter estimates differ across media with significantly different hydrologic characteristics. All tracer tests were conducted by injecting one or more tracers (dissolved or suspended in groundwater) into an isolated interval in one of the C-wells while the corresponding interval in another of the C-wells was pumped. The test intervals in both the injection and production wells were isolated using inflatable packers in the same way that intervals were isolated for hydraulic testing. In each tracer test, a steady flow field was established prior to tracer injection. Tracer tests were typically conducted immediately after hydraulic tests were completed in a given test interval, although hydraulic data continued to be collected throughout each tracer test.

The tracer tests were conducted either in a radial-convergent flow configuration or in a partial recirculation flow configuration. In the latter case, a fraction of the water pumped from the production well was re-injected into the injection well for an extended period of time after tracer injection. For radial-convergent flow tests, there was no water injection after the tracer spike.

Interpretive framework:

To obtain estimates of solute transport parameters in the tracer tests, semi-analytical dual-porosity transport models with appropriate initial and boundary conditions were used to fit the normalized solute tracer responses (Maloszewski and Zuber, 1985; Moench, 1989; 1995; USGS, 2002a; 2002b). For both modeling approaches, it was assumed that tracer transport in fractures can be described by the one-dimensional advection-dispersion equation with one-dimensional diffusion occurring into the surrounding matrix perpendicular to the flow direction in fractures.

Alluvial Testing Complex (ATC)

At the ATC, three single-well injection-withdrawal tracer tests were conducted in the saturated alluvium in the uppermost screened interval of well NC-EWDP-19D between December 2000 and April 2001. For each test, two conservative tracers, each with a different dispersion characteristic, were simultaneously injected, followed by a large volume of tracer-free water. After set periods of time (0.5 hr, 2 days, and 30 days), the well was pumped and the effluent was analyzed for each tracer. From these tests, estimates of the ambient flow velocity, the porosity, and the porosity conceptualization (dual or single) could be made. For these tests, the absence of solute tracer diffusion into the stagnant or nearly-stagnant water indicated that a single-porosity conceptualization of the alluvium was most appropriate.

2.10.3.3 Data Evaluation: Interpretation Methods and Logic

Evaluation of the hydrogeologic performance of the Yucca Mountain site is accomplished through a series of flow and transport models. Of interest to this discussion are the assumptions made in the transport model and how they might effect data collection during the preliminary investigation phase of site-selection. A variety of laboratory and field data supports the understanding of the transport processes of included in the transport model. For example, the cross-hole tracer tests discussed above support the use of a dual-porosity, fracture flow and transport model. Additionally, several laboratory-scale colloid-facilitated Pu transport experiments conducted in fractured volcanic rocks support the use of a colloid-facilitated transport model in the volcanics (Kersting and Reimus, 2003). The overall site-scale transport model is validated by comparison to transit times and flow paths deduced from hydrochemistry data (BSC, 2004b).

Important assumptions and corresponding data requirements for the transport model are:

1. Radionuclides advect and disperse through the fractured portions of the tuffs near the water table. Flow intervals identified in well tests correlate with fracture locations (Erickson and Waddell, 1985), the extent of fracturing correlates reasonably well with the degree of welding (Waddell et al., 1984), and the degree of welding is one of the criteria used to defined sub-members within the lithologic unit.

   Conceptually, high-permeability regions are offset by low-permeability regions due to the extensive faulting and fracturing observed in the volcanics within the model domain (Luckey et al., 1996). These low-permeability zones effectively act as large-scale heterogeneities that give rise to macroscopic dispersion over the scale of hundreds of meters to kilometers.

2. Fluid flow occurs preferentially within the flowing intervals, whereas stagnant fluid resides in the rock matrix. Solutes diffuse into and out of fluid within the rock matrix that is essentially stagnant. This assumption is supported by the tracer tests completed at the C-wells complex.

3. Sorption reactions occur between the rock matrix and some of the radionuclides, tending to retard the transport of these radionuclides. Sorption coefficients (e.g., K_d) are usually obtained from laboratory experiments or field-scale tracer tests.

4. Radionuclides can undergo colloid-facilitated transport. Because of the relatively large size of the colloids, matrix diffusion of these particles is negligible. Several field observations have suggested that a small percentage of colloids transport with essentially no retardation in groundwater (Kersting et al., 1999; Penrose et al., 1990), whereas the majority undergo either reversible or irreversible filtration, which can be described with a retardation factor. The retardation factor is dependent on several factors such as colloid size, colloid type, and geochemical conditions (e.g., pH, Eh, and ionic strength).
5. The radionuclides advect and disperse with the groundwater through the alluvium. Flow is focused through the more permeable regions within the medium and the lower-permeability regions act as flow barriers. This characteristic tends to reduce porosity available to flow and transport as compared to the total large-scale porosity of the alluvium. To account for this, the effective flow porosity of the alluvium is a stochastic variable with a range of input values. Site characterization tests that can shed light on the variance of the log-conductivities of the heterogeneities as well as the correlation length scales are important when assessing the implications of transport through a sedimentary medium.

The transport model incorporates the transport processes of advection, dispersion, diffusion, retardation, and colloid-facilitated transport to compute the downstream radionuclide concentrations. Key input parameters to the transport model are dispersivities, matrix porosity, K_d, flowing interval porosity, flowing interval spacing, flowing interval aperture, retardation factor in the flowing interval, bulk density, and effective porosity. Each of these parameters is estimated for each rock type and for inter- and intra-matrix regions as appropriate.

2.10.3.4 Interpreted Importance of Individual Parameters

At the regional level, the parameters most important for making legitimate screening decisions are those that (Luckey et al., 1996):

- Facilitate accurate calculation of the overall water balance
- Determine flow rates and directions
- Determine the groundwater age and residence times

As an area is dissected into site-scale domains, scale dependent parameters become important both conceptually and probabilistically. The importance of a given parameter (e.g., horizontal permeability anisotropy; radionuclide sorption coefficients) can only be illuminated within a systematic framework that can objectively test the sensitivity of the conceptual model to multiple input parameter sets (BSC, 2004c). Thus, it is difficult to specify ahead of time a prioritized list of parameters without first determining the key system components. This has been completed for the Yucca Mountain repository TSPA-LA through systematic evaluation of features, events, and processes (FEP's) (BSC, 2005). The lists of included and excluded FEP's that are analyzed are given in Table 10.

Table 10 − Features, events, and processes (FEPs) treated through sensitivity analyses in the saturated zone abstraction model for the Yucca Mountain repository TSPA-LA. The highlighted FEP's are directly related to concerns over active tectonic changes to the geological barrier description and time-dependent assumptions.

<u>Included FEP</u>	<u>Excluded FEP</u>
1. Fractures: spatial distribution, parameterization	1. Igneous activity changes rock properties
2. Faults: spatial distribution, parameterization	2. Ash redistribution in groundwater
3. Water table rise (climatic variability)	3. Hydrothermal activity
4. Water management activities	4. Large-scale dissolution
5. Well usage	5. Hydrologic response to seismic activity
6. Stratigraphy: uncertainty in distribution	6. Hydrologic response to igneous activity
7. Rock properties of host rock and other units	7. Water table decline
8. Saturated groundwater flow in geosphere	8. Recycling of accumulated radionuclides from soil to groundwater
9. Water-conducting features in SZ	9. Transport of particles larger than colloids in SZ
10. Advection and dispersion in SZ: parameterization	10. Seismic activity changes porosity and permeability of (i) rock, (ii) fractures, or (iii) faults
11. Dilution of radionuclides in groundwater	11. Chemically-induced density effects of groundwater flow
12. Diffusion in the SZ	12. Geochemical interactions and evolution in the SZ
13. Fluid geochemical profiles in the SZ	13. Radionuclide solubility limits in the SZ
14. Complexation: parameterization	14. Groundwater discharge inside the reference biosphere
15. Matrix diffusion in the SZ: parameterization	15. Groundwater discharge outside the reference biosphere
16. Sorption in the SZ: parameterization	16. Microbial activity in the SZ
17. Colloidal transport parameterization	17. Thermo-mechanical stresses alter characteristics of(i) rock, (ii) fractures, or (iii) faults near repository
18. Natural geothermal effects on flow in the SZ	18. Thermo-chemical alteration (solubility, speciation, phase changes, diagenesis) in the SZ
19. Undetected features (e.g., hidden faults)	19. Repository-induced thermal effects on flow in the SZ
20. Radioactive decay and in-growth	20. Gas effects in the SZ
	21. Isotopic dilution

2.10.3.5 Key Parameters Affected by Active Tectonics

The FEP's highlighted in Table 10 describe the current thinking on repository safety assessment with respect to the perceived threat of active tectonic forcings in the Yucca Mountain region. The choice to pursue explicit sensitivity analyses for some of these issues reflects the expert guidance on probabilistic likelihood estimates associated with each scenario given the tectonic system and current understanding of future hazards on the 10,000-year timeframe. Excluding the catastrophic event of repository breach by a fault or igneous body, these FEP's generally can be considered as aspects of two themes pertinent to flow and transport modeling:

- Horizontal anisotropy in permeability, and
- Systematic groundwater flow response to future emergent volcanism that produces significant igneous intrusions in the site-scale area.

It should be pointed out that the FEP's used in the YMP focus on the site-scale effects and are not necessarily applicable to the initial regional-scale assessment. The conceptual model should account for possible FEP's, only ruling out those that can be confirmed insignificant through data or expert judgment. As the site-selection process moves from the PIA level to the DIA phase, added data collection, modeling activities, and the like, will reveal the insignificant FEP's.

2.10.3.6 Remaining Uncertainties Identified

The key uncertainties associated with long-term safety predictions at Yucca Mountain are:

- Groundwater transport times
- Degree of channelization (fracture or fault-preferred) in groundwater flow
- Matrix diffusion parameterization from the standpoint of radionuclide sorption, active flow volume, and interaction with fracture flow systems
- Redox conditions in the SZ
- Climatic variations and groundwater flow

These are issues that span the entire analytic process:

- Data acquisition: spatial coverage, accuracy, and scale-dependencies
- Model abstraction: inclusiveness of all processes, accuracy of mathematical representation, and model parameterization
- Numerical simulation: spatial resolution and absolute accuracy

2.10.4 Issues Remaining to be Answered

The TSPA-LA process is ongoing. For the Yucca Mountain repository, no broad issues of major significance appear to be outstanding, but license authority for construction is still under review.

2.10.5 General Comparison of Site Selection Process with NUMO's Process

The United States government's approach to selection of Yucca Mountain as its single site for HLW repository characterization bears little resemblance to that pursued by NUMO. To a large extent, the placement of the repository reflects three dominant factors:

1. Siting the repository in as remote an area as possible, subject to transportation considerations (minimal population density cumulative dosage risk to the populace)
2. Belief that a thick UZ offers enhanced geological barrier performance relative to containment directly in a saturated hydrologic system
3. Governmental control of vast areas in the Nevada desert immediately surrounding the proposed site (e.g., Nevada Test Site)

It is important to note that any such 'decide and defend' approach, if pursued in the current socio-political climate in the U.S., could lead to the common end experienced in the United Kingdom (e.g., Sellafield) and Germany (e.g., Gorleben); a public backlash and subsequent collapse of the process.

2.10.5.1 General Characteristics

Geoscientific characterization over almost three decades has been undertaken to ensure that the risks of HLW disposal are quantifiably understood. The duration required to properly describe the repository and geosphere-biosphere interactions has meant that multiple political landscapes have been involved in shaping the current TSPA-LA product. It is important to note, however, that repository characterization science was in its infancy when Yucca Mountain was moved forward to site-scale study. Key advances that should greatly speed the progress toward siting a repository in Japan include:

- Better mathematical conceptualization
- Increased resolution in numerical calculations (model domain and accuracy)
- Better understanding of vadose zone flux, flow, sorption, and transport process science
- Better understanding of biosphere sorption and dose-response processes

2.10.5.2 Interaction with Public and Distribution of Programmatic Information

As mentioned previously, the beginnings of the HLW repository selection process in the United States does not resemble the socio-politically modern model in use by Japan, whose process itself is similar in principle to the procedures being followed (or hoped to be followed) in many of the western European nations. At least part of the success of the HLW siting process in the U.S., however, can be attributed to the adaptation of the Department of Energy (and other agencies involved) to the demands of the public for input and full disclosure. This has been accomplished through the Office of Civilian Radioactive Waste Management website (OCRWM, 2006), frequent publications of key research in peer reviewed journals, periodic press releases, and systematically produced summary reports.

3 International Program Summary

This section briefly considers some of the range in characteristics of international waste-management programs with specific comparison to the Japanese program.

3.1 Interactions Among Organizations and Processes

Figure 6 summarizes many of the conceptual interactions among five key elements involved in siting, characterization, and development of a nuclear-waste repository. The intent of this discussion is only to consider some of the possible options in each of the areas.

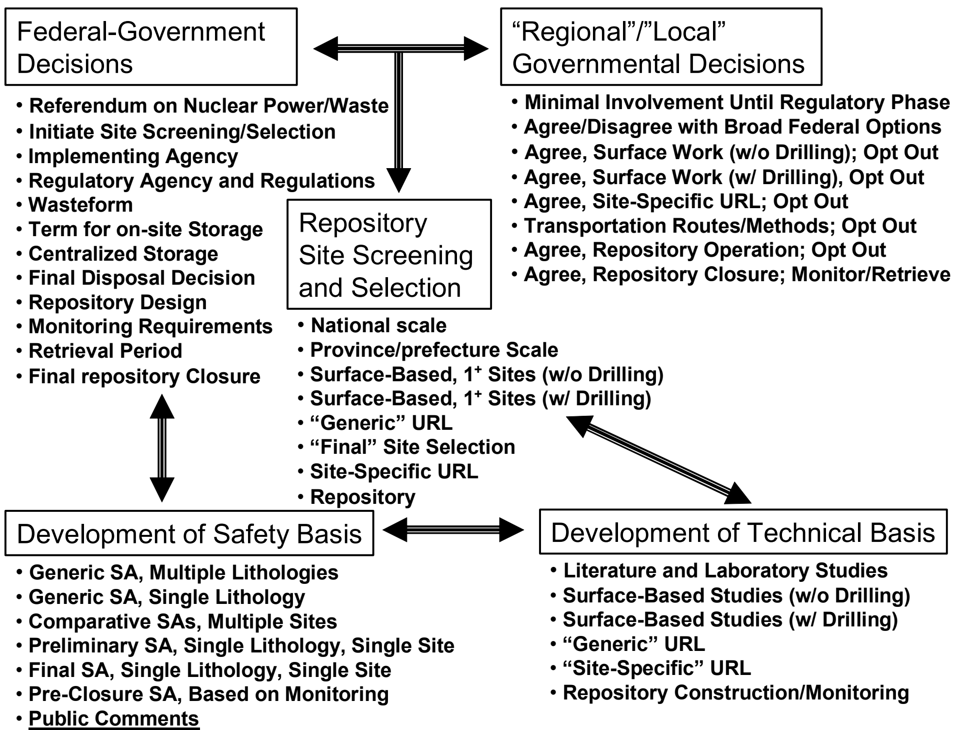

Figure 6 - Conceptual interactions among key elements related to site screening, selection, and characterization for a nuclear-waste repository.

3.1.1 Guidance from Federal Governments

Federal governments are the initiators of waste-management or repository siting activities at the national scale. Certainly, it is the initial function of the federal government to begin site-screening/selection activities, determine both the implementing and regulatory federal agencies, and define the wasteform(s) to be considered in both repository design and safety/regulatory assessments.

One factor complicating site selection is that if a country has developed significant nuclear power before waste-disposal issues gain public attention, some of the options are *de facto* eliminated from consideration. The governmental decision to reprocess HLW has already been implemented in Japan; therefore, the option of disposing of un-reprocessed spent fuel is no longer open. However, beyond the basics, a broad range of approaches has been attempted worldwide. A few of the variations in approach are considered here.

Regarding the initial range of options open for consideration.

One characteristic of initial federal guidance is that it generally assumes that deep geologic disposal is the preferred option, and that this option should be pursued aggressively. Variations from this underlying assumption appear to have arisen only in response to public interactions. With the exception of Belgium and Canada, initial planning calls for strong coupling of experimentation and the disposal decision.

Regarding initial public interactions.

In the American approach (Yucca Mountain), initial public involvement was minimal. The major decisions were considered to be strictly a federal responsibility because the proposed repository site is on federal land. At the other extreme in Sweden, a national referendum was held on nuclear power and nuclear-waste disposal relatively early in the process.

Regarding initially planned iterative public interactions.

In the American approach (Yucca Mountain), major public interaction was not considered in original planning. In many other programs, including the Japanese program, present planning calls for iterative interactions among local governments, regional governments, the population at large, and the federal program. However, these interactions can be either before-the-fact or after-the-fact. In Sweden, before-the-fact local referenda led to involvement of six volunteer communities in the process; two of these later withdrew from consideration, also by referendum. In Finland, the local municipal government granted the construction license for a site-specific URL. In Great Britain, the local government stopped the planned underground program at Sellafield. This happened, however, after the Sellafield site had been selected by the federal government without public participation in the process. In Switzerland, a local referendum stopped planned development of the Wellenberg site (ILW).

In Spain, after-the-fact local protests, in response to publication of a list of potential site areas, led to abandonment of site-screening efforts in granitic rocks. In Canada, the unexpected inclusion of major social issues, during public hearings held in response to publication of a formal Environmental Impact Statement (EIS) for the planned concept of waste disposal led to complete redirection of the program.

Regarding the ultimate range of options for consideration.

In some cases, public interactions or changes in federal government, have led to major redirection of federal waste-disposal programs. These redirections have consistently broadened the range of options considered. In Canada, critical response to the conceptual EIS, prior to any site-screening activities or significant public interactions, led to a forced consideration of a very broad range of approaches, including lengthy on-site storage of waste, centralized surface storage, extensive monitoring periods in surface facilities and/or in a deep repository, and extended periods of waste retrieval in a deep geologic repository.

A similar range of options is now being considered in Great Britain after the project at Sellafield was stopped by the local government. In Germany, a change in national government led to both abandonment of the existing Gorleben disposal facility and reconsideration of a broad range of options. In Spain, the protests at potential site areas in granitic rocks led to greatly increased participation in international generic URLs, especially at the Äspö (Sweden), Grimsel (Switzerland), and Mol (Belgium) URLs.

It is difficult to draw generalities from the range of international experience, in part because of the different stages of the programs. However, it appears, with benefit of hindsight, that the most successful programs have been those that have had the largest amounts of preliminary public involvement. It also appears that at least the level of general public acceptance increases as the range of options considered increases. One potential problem, given that re-directed programs are still at relatively early stages in their revised processes, is that increased public acceptance early in the process does not necessarily equate to the ability to make repository-siting decisions later on.

In the Japanese case, the *Specified Radioactive Waste Final Disposal Act*, (June, 2000) requires a major effort in identifying and working with local communities in the attempt to identify possible candidate sites. However, this Act also significantly restricts the ranges of options presently considered open for consideration. For example, as summarized by NUMO (2004):

> *"The Act is also prescriptive in terms of the management option to be followed. It specifies deep geological disposal in Japan at depths greater than 300 m below (the) surface. Also specified are requirements for geological stability and avoiding conflict with natural resources. The phased process of developing a siting project, involving more detailed characterization as options are narrowed down, is also outlined in the legislation."*

Thus, the present Japanese program appears to effectively combine the preliminary narrowing of options similar to that of the Canadian program with both off-site or generic URLs and favorable preliminary safety evaluations (H12) and an active outreach program, similar to those of the Swedish and Finnish programs. The Japanese outreach program has been implemented somewhat later in the process than in the case of either Sweden or Finland, but certainly earlier than in the Canadian program.

3.1.2 Decisions by Regional and Local Governments

As shown in Figure 6, there are several stages or steps that logically involve the regional and local governing bodies. Most of the entries in the list simply parallel the sequence of local events in the area of repository site screening and selection (at the center of the page). It is not clear from the existing documentation to what extent formal consideration of public/local comments in response to safety documentation developed during the site-screening and site-selection processes is planned by the Japanese program (NUMO, 2002a).

The assumption in Figure 6 is that for a program to be successful in the long run, the process of repository site screening and selection must be directed jointly by the federal government and some combination of regional and local governments. The details of the process, and specifically the detailed roles of the different levels of government will vary from country to country. For example, the present German planning explicitly calls for numerous national referenda during the overall process, and in case of a major stalemate, refers decisions to authorities at the federal level.

3.1.3 Site Screening, Selection, and Characterization Process

In a few countries (e.g., Finland) the site-selection, -screening, and -characterization processes are straightforward series of steps, extending from the national to the site-specific scales, as the project proceeds. This is analogous to the approach presently planned by the Japanese. In other countries, such as Great Britain and the US, site selection was strongly influenced by the desire to have facilities in federally controlled areas already dedicated to nuclear activities. In some countries (e.g., Belgium, Canada, and Spain), site-selection processes are not formally active. In programs involving a formal screening process, the main variations appear to be in: a) the formalism of criteria used in the screening/selection process; and b) the site-characterization process at multiple sites.

Regarding types of criteria used in site screening and selection.

In some cases (e.g., France), most of the criteria are relatively qualitative. For example, the French state that a potential host rock must have favorable geochemical conditions that limit the mobility of the radionuclides, and a low diffusion coefficient. This type of criteria provides general guidance, but is not specific.

The use of exclusion criteria is also common. For example, the German criteria stipulate that there shall be no active fault zones in the repository area, and that large-area vertical movement must be < 1 mm/yr over the predictable period.

Several programs, including the German, Belgian, and French programs, impose minimum requirements. For example, the German program requires that the isolating rock zone thickness must be > 100 m, and that is must be comprised of rock to which a field hydraulic conductivity of $< 10^{-10}$ m/s can be assigned.

A few programs, notably the German and Japanese programs, also consider favorability criteria. These relative criteria, expected to play a role in selection of the final site, include such things as required waste-transportation distances and expected difficulty or cost required for adequate rock mass characterization.

Regarding the extent of site characterization at multiple potential sites

The Swedes are conducting extensive characterization work at both the Forsmark and Simpevarp sites, prior to final site selection, though it is not clear whether this was planned, or is a consequence of some delay in final site selection. In addition, the Swedes have conducted extensive experimentation in two generic URLs, Stripa and Äspö. The Germans plan on conducting underground experiments at two on-site URLs, prior to final site selection.

In contrast, in Finland, underground experimentation will be conducted in the ONKALO on-site URL, only after final site selection. In some cases, the planned extent of underground testing relative to the site-selection process is simply not clear at this time. Although extensive work has been done in the Mol URL, Belgium has not formally begun its site-selection process. However, nothing legally excludes the Mol facility from becoming a repository.

3.1.4 Development of Technical Basis for Disposal

The initial governmental approaches to nuclear-waste disposal all seem to be based on the assumption that it is largely a technical issue. Thus, development of the technical basis for waste disposal generally seems to be the first area where activity begins. The initial stages of the site-screening process are often carried out using technical criteria only, in the absence of both formalized regulatory or safety criteria and significant interactions with regional and local governments.

There is, however, one major variation among the programs considered here, specifically the extent to which use is made of one or more generic or off-site URLs. Conceptually, these facilities are intended to increase the technical and procedural understanding in generic rock types prior to final site selection. There are many such facilities worldwide, including, for example, the Whiteshell URL in Canada, Grimsel and Mt. Terri URLs in Switzerland, Asse and Gorleben mines in Germany, and both the Stripa mine and Äspö URL in Sweden. In Japan, the extensive generic experimentation carried out at both the Tono (layered sedimentary rocks above granite) and Kamaishi (granite) mines played a significant role in developing the technical base for waste disposal, as demonstrated in the H12 series of documents (JNC, 2000).

Because potential PIAs and DIAs have not yet been identified by the Japanese program, the issues of what data and interpretations are and are not transferable from generic test facilities to site-specific studies cannot yet be addressed in concrete terms. However, judging from recent documentation, NUMO has avoided the possible pitfall of viewing future work in one or more PIAs and DIAs as being confirmatory (NUMO, 2002b). Instead, the terminology is to the effect that this work will be for purposes of characterization.

While the technical objectives for generic URLs generally are met, the use of the conclusions resulting from work in them is not without significant risk. As demonstrated in Canada, the favorable technical conclusions resulting from work at Whiteshell were not sufficiently matched by public confidence to allow the program to proceed as planned.

3.1.5 Development of Safety and Regulatory Basis

As shown in Figure 6, there are two major sources of input to the federal government. One discussed already is the reciprocal input from regional and local governments (intended here to include the population at large). The other is documented safety assessments or evaluations. A formal site-specific assessment is uniformly required prior to repository licensing. However, some level of safety evaluation is also an integral part of most site-screening processes.

In Finland, a preliminary safety assessment was carried out prior to final site selection, but failed to draw any significant distinctions among the four sites considered; i.e., favorable results were calculated for a repository at all potential sites (Vieno and Nordman, 1999). Although the all-favorable nature of the results seems to be characteristic of such documentation, this assessment does not appear to have impacted the program negatively. In contrast, the general response to the Canadian EIS, which contained similarly positive technical conclusions, was quite negative. The reasons for the differences in response are not clear.

3.2 Parameter Prioritization

The general terminology used here to lump the broad range of rock types of interest for a final repository is imprecise, at best. The entire range of rocks is simply divided into hard-rock and soft-rock, not on the basis of relative matrix strength, but on the basis of the relative uniformity of the rock type (layering) and both porosities and permeabilities of the matrix. Relatively massive rocks with low matrix porosities and low matrix permeabilities are considered as hard rock. From this perspective, this includes anomalous rock types such as halite (Germany) and the Boom Clay of Belgium. In contrast, inherently bedded rock types, such as both bedded Tertiary sediments (France) and welded tuff (USA), are considered soft rock, regardless of their matrix strength.

In the near-field environment, layering and related porosity/permeability contrasts play a larger role in soft rock. Radionuclide release to the far-field may be through either the matrix of the rock mass or along bedding contacts. From a site-characterization point of view, however, soft rocks generally require less detailed information than hard rock sites, simply because the variability within the rock mass is inherent and/or stratigraphically controlled. The lateral continuity of bedding/layering structures is relatively reliable, allowing more reliable three-dimensional projection of geologic structures.

In fact, it generally appears that the decreased site-characterization requirements for soft rock have led to the tentative conclusion that there are relatively few remaining technical needs with the exception of being sure that possible structural-deformation zones have all been identified. In the case of Belgium, there is concern with confirmation of expected lateral continuity of stratigraphy within the inherently bedded Boom Clay, and with the possible effects of permeable sands both overlying and underlying the disposal horizon. In addition, there is concern (Spain) about the possibility of colloid formation in the local groundwaters and the impact this may have on radionuclide transport.

Non-inherent or non-lithology-specific fractures and deformation zones play a much larger role in low-porosity hard rock environments. At the site scale, these structures are essentially controlled by the local tectonic regime and history rather than by the lithology. In the case of granitic rocks, however, there are also generic fractures at the small scale resulting from cooling or uplift. There is general concern in hard rock programs that a better understanding of the statistical characterization of flow and radionuclide-transport parameters are needed before the structures being modeled can be based on stochastic rather than deterministic models. The welded tuffs at Yucca Mountain (USA) are in some respects a mixture of hard and soft rock types. In general, fracturing in these units, resulting primarily from cooling, is proportional to the degree of welding. In addition, however, Yucca Mountain is in a seismically active region, making tectonic fracturing a significant factor.

The single greatest remaining technical needs in the hard rock programs evaluated here are for determination of the properties, lateral continuity, and interconnectivity of identified high-permeability zones. Because these zones are generally structurally- rather than lithologically-controlled, the amount of site-specific characterization work required for this definition is large. In addition, it has been noted (especially in the Finnish program) that there is only limited correlation between the site structural or rock mass model, based largely on downhole coring, and the site hydrologic model, based on downhole testing. This is because many of the existing fractures identified in cores are effectively sealed by secondary minerals. In contrast, in the Yucca Mountain program (which is in the unsaturated zone), there is good correlation between fracture frequencies observed in core and *in situ* transmissivities. There is also general concern in both hard-rock and soft-rock sites that regional-scale and site-scale groundwater modeling would benefit from increased integration of flow and chemical-evolution models for the groundwater.

An additional apparent paradox should be mentioned. While far-field flow and transport in low-porosity hard rock is expected to be controlled by discrete deformation/fracture zones, extrapolation of the results of the TRUE tracer tests in the Äspö URL in Sweden indicates that even in this rock type, long-term radionuclide retardation will be controlled by matrix porosity under normal-gradient conditions (rather than being controlled by discrete high-permeability pathways and easily accessible near-fracture porosities). Therefore, there is a recognized need for improved understanding of long-term processes within hard-rock lithologies.

It also should be noted that in some countries the major issues at this time are political/social and/or procedural rather than technical. For example, site-selection activities have stopped and have yet to be re-started in Canada and Spain (granitic rocks). In France, it has proven impossible to get approval for even a generic URL in granitic rocks. The German and British programs are still in the relatively early stages of major re-starts. In Belgium, formal site-selection activities have yet to begin. In short, at least in these countries, social and/or political issues seem to outweigh any technical issues at present.

3.3 Active Tectonics and Hydrologic Parameters

Conceptually, there are at least five possible areas of concern with neotectonics and/or future tectonics and their possible impact on repository performance. This section briefly discusses these areas of concern. The considerations do not include generation and removal of any Excavation Damages Zone around the repository and/or emplaced seals and plugs.

<u>Uplift/Exhumation</u>

In areas of active tectonic uplift, such as parts of Japan, there is concern that natural uplift over the timescales of interest in disposal of high-level nuclear waste (nominally ~100,000 years) could exhume the repository, leading to direct exposure of the waste containers on the land surface.

The Japanese program has addressed this issue by excluding areas from consideration, when there is evidence for more than 300 m of uplift over the last 100,000 yrs (NUMO, 2002c). An analogous constraint on uplift rates exists for the German program. In contrast, significant regional uplift is expected in the Swedish and Finnish program, as part of glacial rebound.

<u>Seismic Activity or Disruption</u>

There is a general concern that future tectonics might disturb a repository due to direct seismic activity or movement. There are two general areas for this concern: a) excavation stability (and constructability) prior to closure; and b) possible disruption of emplaced waste and/or waste containers.

The Japanese program has also addressed this issue by defining potential Preliminary Investigation Areas (PIAs) as "excluding locations with active faults identified by nationwide literature, based on aerial photographs for inland areas and sonic profiling for offshore (areas)". In a preliminary literature review, no consideration is given in the Japanese program to allowable distances or offsets from active faults. Their presence is solely used as a disqualifying criterion for any potential PIA. The underlying or implicit assumption appears to be that adequate repository volumes can be identified and characterized that will contain no active or potentially active faults.

The Swedish program has taken a significantly different approach to evaluation of seismic stability. The Swedish, Finnish, and Canadian underground experience consistently indicates that deformation structures having the potential for future re-activation will be present at the repository scale, at least in granitic rocks in shield areas. This conclusion may or may not be applicable to rocks intruded into non-shield areas, such as the mainland of Japan, though the non-shield areas are inherently more tectonically active.

Given the necessary assumption that potentially active faults will be present at the repository scale, the Swedish program has defined respect distances (i.e., distances from reliably identifiable fault/fracture structures) within which no waste container can be placed. This appears to be one area in which simple exclusion of possible PIAs by the Japanese program, on the basis of the presence of active faults may be overly restrictive.

Hydrology – Changes in Properties of Deformation Structures

In hard rock programs, especially in Sweden and Finland, considerable attention has been paid to identification and characterization of potentially permeable deformation zones (ductile, brittle, or reactivated structures). The general belief is that future faulting would involve reactivation of existing structures, although the Swedish program considers the possibility that future faulting might involve coalescence of existing fractures into an intrusive fault at the repository scale.

It was also noted that while reactivation of pre-existing structures is believed to dominate, there is no conceptual or numerical model relating either the extent of movement in any single activation episode or the total number of reactivations to the permeability of the fault/deformation zone. Instead, the approaches taken in both the Swedish and Finnish programs to assigning permeabilities to deformation zones for purposes of safety assessment are empirical. Specifically, in progressing from field experiment/measurement to analysis, the field data are generalized into a single depth-dependent trend of permeability versus depth.

This review has not identified any example or planning indicating the intent to consider changes in the permeability of identified deformation zones in response to possible future tectonics. Nor, with the sole exception of the Yucca Mountain program (USA) has any documentation been found explicitly excluding such changes from consideration.

Hydrology – Changes in Head Distribution

The distributions of hydraulic heads in hard rock systems seem to be completely controlled by the modeled zones of relatively high permeability. While the search has not been as extensive as that regarding changes in properties, this review has not identified any example in which changes in hydraulic head have been considered in response to possible future tectonics.

Hydrology – Changes in Groundwater Composition

It is conceptually possible that future faulting, if it were to generate new, relatively high-permeability pathway's through the repository, might also lead to introduction of groundwaters of new composition; i.e., of either higher or lower salinity and/or higher or lower potential for colloid formation. Although no consistent search has been made, the only consideration of this possibility found to date is within the Spanish program, where the possibility of possible changes in colloid-formation potential or content in response to faulting is noted.

3.4 World Wide Conceptualization

While several programs account for tectonic processes that are localized in nature, such as glacial rebound, dike intrusions, or the like, no international HLW program is addressing active tectonics on a regional scale. This implies that every HLW program uses the same conceptualization in regards to this issue. This conceptualization can be stated as:

> *The present geological state is stable and there is no need to consider changes in structural and mineralogical features and their impact on the flow and transport over long periods of time.*

This does not imply that this conceptualization is the correct approach for Japan. Instead, it reflects the fact that the HLW programs outside of Japan do not have the geologic conditions that would force a different conceptualization. Conversely, this also does not imply that Japan *must* include active tectonics in its PI investigations, but rather, indicates a need for further investigation.

4 Peer-Reviewed Literature

This section represents a summary of the peer-reviewed literature that discusses active tectonics and its effects on groundwater flow, which are outside the international HLW programs reviewed above. Most of this research addresses near field effects and/or the effects immediately prior to or immediately after a seismic event. While most of these studies are interesting from a scientific view, they are not readily applicable to the question of how active tectonics may affect hydrogeological conditions over the long-term and at the regional scale. However, examination of these documents does reveal some common elements that may be useful to NUMO's site-selection process.

4.1 Crystalline Rock Environments

It has been well documented that hydrologic changes occur in response to earthquakes and active tectonics (Muir-Wood and King, 1993; Sibson, 1981). Many studies have examined the hydrological impacts of specific events (e.g., Grecksch et al., 1999; Huang et al., 2004; King et al., 1999; O'Brien, 1992; Quilty and Roeloffs, 1997; Roeloffs et al., 1995; Rojstaczer and Wolf, 1992; Tokunaga, 1999), with most of these concentrating on the pre-, co-, or post-seismic time frames. Several studies examine the surface water response, such as changes in river levels and/or spring flow (e.g., Curewitz and Karson, 1997; Léonardi et al., 1998) and a relatively small number of studies have addressed at some level, the geochemical changes due to seismic events (e.g., Quattrocchi et al., 2000; Satake et al., 2003; Tokunaga, 1999).

More generally, other studies have attempted to establish a relationship between the stress-strain field and hydrologic parameters (e.g., Barton et al., 1995; Ge and Cheree Stover, 2000; Gudmundsson, 2000; Liu et al., 2000; Tröger et al., 2001; Wang and Park, 2002) with several attempts at modeling or assessing the stress-strain impact in one form or another (e.g., Fairley et al., 2003; Ge and Cheree Stover, 2000; Kitagawa and Koizumi, 2000; Tokunaga, 1999; Zhang et al., 2002). What is common amongst most of these studies is the short-term nature of the investigated transient, with water levels and/or spring flows returning to pre-seismic levels over times ranging from almost immediately to up to a year. The exception is Tröger et al. (2001), who use analysis of fault planes, joint patterns, and stylolithes to infer six paleo-stressfields of the Algarve Basin in Portugal. However, the time-scales associated with these stress-fields are well beyond the 100,000-year standard for the storage of HLW. The lesson here is that there appears to be no evidence to support or reject a conceptual model that includes the long-term influence of active tectonics on the regional hydrogeology.

One set of studies that provides additional insight are those by Yoshida et al. (2000; 2005), and Yoshida and Takeuchi (2004). Yoshida et al. (2000) point out that an understanding the long-term stability of the geological conditions in Japan, and the impact that active tectonics may have on the ability of a rock environment to retard the movement of radioactive waste, must be developed in order to build confidence in the quantitative assessment of long-term repository behavior. Yoshida and Takeuchi (2004) further state that in regards to the underground storage of HLW, current conceptual models only take into account the present geological state and do not account for changes of structural and mineralogical features and their impact on the flow and transport over long periods of time. This viewpoint is clearly supported by the results of the literature review of the International HLW programs presented above.

The latter two studies (Yoshida and Takeuchi, 2004; Yoshida et al., 2005) describe a comparative study of the fracture characteristics of three differently aged granitic plutons (1.9-0.8 Ma, ca. 67 Ma, and ca. 117 Ma) located in the orogenic continental margin in Japan. The studies begin by characterizing the long-term growth-pattern and the rate of generation of new fractures by comparing the fracture characteristics of the different aged plutons. The results suggest that the crystalline rocks of Japan seem to have similar fracture characteristics that are independent of age and/or location. Furthermore, by examining the layered fracture fillings that are formed by the water/rock interactions, they found that within the three plutons, fractures were primarily formed during cooling and uplift. This implies that a natural 'background' level of fracturing is inherent in most of the crystalline rocks and that these background fractures tend to act as stress relieving features over time. In other words, new movements will re-activate pre-existing fractures rather than create new fractures. This conclusion is indirectly supported by Bäckblom and Munier (2002).

With regards to the long-term storage of HLW, these results imply that the current conceptual model, which assumes hydrogeological stability over time, may be sufficient. However, Yoshida et al. (2005) also conclude that the background fractures and the determination of 'background fracture frequency' are important parameters that need to be understood for plutons in an orogenic environment.

4.2 Volcanic Environments

None of the literature involving active volcanism that was reviewed here (Courteaud et al., 1997; Custodio, 1989; Folio, 2001; Iverson, 1995; Join et al., 2005; Lenat et al., 2000; Mastin, 1997) addressed hydrology and/or hydrogeology beyond a 15 km radius of a volcanic center; the 15 km representing the exclusion zone for a site to be eligible as a PIA (NUMO, 2004). Thus, there appears to be no immediately available research into the long-term impact of active volcanics on flow and transport at the far-field.

For a repository site, active volcanism is generally addressed as a 'feature, event, or process' (FEP) within a performance assessment (PA) model (BSC, 2005). In this case, a volcanic feature, such as a dike intrusion into the repository (see Table 10), is conceptualized as one of the possible futures in the PA model. Probabilistic parameters determine the likelihood of such an intrusion and the PA modeling determines the outcome of that event. While applicable for detailed site investigations, this approach is not needed at the preliminary stage.

5 A Suggested Method for Identifying Key Hydrological Processes and Parameters

The N^2-impact matrix, or interaction matrix, has been frequently used in the field of systems engineering to help identify the interactions or interfaces between major factors from a systems perspective. In the field of rock mechanics, rock engineering and underground construction, the N^2-impact matrix is sometimes referred to as the Rock Engineering Systems or RES (Hudson, 1992).

In order to establish the required variables and linking mechanisms for a HLW disposal model, the RES methodology has been used on both the Swedish (Stephansson and Hudson, 1993) and UK Nirex programs. The N^2-impact matrix approach was also applied to assess the direction and scope of future work toward the development of an HLW repository in Korea (Sorenson et al., 2000).

The framework for the recommended Total System approach was developed at Sandia National Laboratories (SNL) for managing and prioritizing the scientific and engineering technical efforts that led to the certification of the WIPP repository—the only certified and operational HLW repository in the world. The framework represents numerous man-years of valuable experience that also was transferred to the Yucca Mountain project in the United States. Based on the demonstrated success in the United States of the Total System approach and Systems Prioritization Analysis (SPA), the N^2-impact matrix it is recommended as a possible approach to assure continued success for the Japanese repository development.

5.1 N^2-Impact Matrix (Rock Engineering Systems)

As shown in Figure 7, the N^2-interaction matrix or the $N \times N$ RES interaction matrix consists of N leading diagonal components and ($N^2 - N$) off-diagonal components. The leading diagonal components, A_{ii} (where i = 1 to N), represent the parameters or the major subjects of the system (e.g., T=Thermal, H=Hydrological, and M=Mechanical couplings) to be investigated. The off-diagonal components, A_{ij} (where i,j = 1 to N, $i \neq j$), represents the linking mechanism (interface or impact) of the major parameter A_{ii} on A_{jj} and is sometimes called the one-way interaction component. The interaction matrix is not usually symmetric since interaction A_{ij} is not always same as A_{ji} under normal situations. Once the diagonal parameters, A_{ii}, are set, then the N^2 diagram forces us to consider each interaction component, A_{ij}, to complete the matrix system. Therefore, the interaction matrix can be used as a thinking tool to construct a system using parameters and linking mechanisms between those parameters.

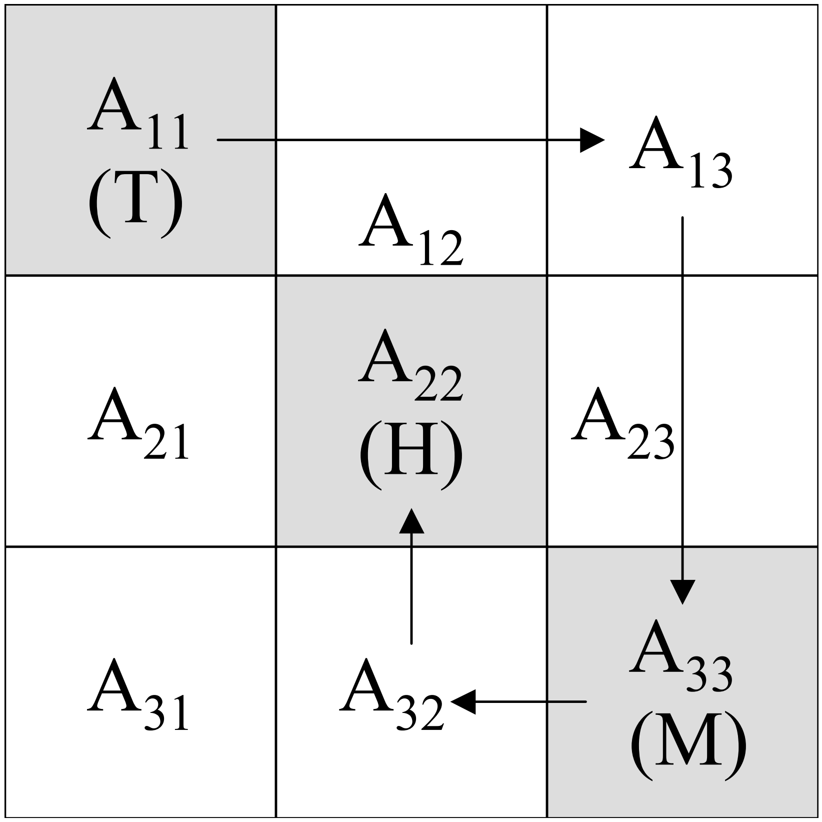

Figure 7 – A 3 × 3 diagram showing the main parameters (e.g., T, H, and M) as leading diagonal components (A_{11} to A_{33}) and the interactions as off-diagonal components (A_{ij} where *i*,*j*=1 to 3).

5.1.1 Quantitative Prioritization of Main Parameters

In order to develop a quantitative prioritization scheme using the N^2 Diagram, the interaction terms shown as off-diagonal elements on the N^2-impact matrix should be coded depending on the degree of interaction. It would be ideal if the degree of interaction is identified based on the linking mechanisms. However, it is usually the case that not enough numerical relationships are identified to asses the impact of one parameter to another. Hudson (1992) suggested an 'Expert Semi-Quantitative' or ESQ scale to quantify the degree of interaction. In this example, there are five categories into which the mechanism can be placed ranging from zero to four. Table 11 shows the ESQ-rating and the corresponding degree of interaction.

Assigning the ESQ rating system to describe the degree of interaction between the main parameters is a subjective process depending on the expert opinion of individuals participating in the process. To meet the stringent requirement of traceability imposed by the regulator, an expert judgment elicitation process (Hora et al., 1991) can be implemented to document the process of the ESQ-rating.

Expert judgment is a part of virtually all scientific endeavors. Decisions must be made regarding how to evaluate a particular hypothesis, how to set up and conduct an experiment, how to interpret the experimental data and which conceptual model to use with the data. Certain aspects of science that require expert judgment may be quite important because they strongly impact other results. For example, the analysis may be pursued while there is still an incomplete experimental data set; the existing data may need to be interpreted before use; or the results could be very important to decision makers and other interested parties. Under these conditions, a formalized expert-judgment elicitation process (from individual experts or a panel of experts) may be useful, and the outcome of this process can often be expressed as quantifiable numerical information. Formalized expert judgment has been used in areas such as nuclear-reactor risk studies (e.g., EPRI, 1989; Hora and Iman, 1989) and a study of human intrusion into a nuclear-waste repository (Hora et al., 1991).

Table 11 − Expert Semi-Quantitative (ESQ) rating system.

ESQ-rating	Degree of interaction
0	No interaction
1	Weak interaction
2	Medium interaction
3	Strong interaction
4	Critical interaction

5.1.2 Dominancy and Interactivity of Main Parameters

Figure 8 shows a N^2-impact matrix showing how the main parameters (A_{11} to A_{NN}) are evaluated quantitatively using dominancy and interactivity properties. The overall impact of a main parameter, A_{ii}, on the other main parameters in the system can be measured by a dominancy factor D_i as follows:

$$D_i = \sum_{j=1}^{N} A_{ij} - A_{ii} \quad \textbf{(6)}$$

The dominancy factor D_i, for A_{ii}, is a summation of the entire off-diagonal component, A_{ij} (where $j = 1$ to N, $i \neq j$) on row i.

The overall interactivity of a main parameter, A_{jj}, from other main parameters in the system can be measured by an interactivity factor I_j as follows:

$$I_j = \sum_{i=1}^{N} A_{ij} - A_{jj} \quad \textbf{(7)}$$

The interactivity factor I_j, for A_{ii}, is summation of the entire off-diagonal components, A_{ij} (where $i = 1$ to N, $i \neq j$) on column j. This summation of the off-diagonal components represents the overall interactivity of the major parameter A_{ii} on A_{jj}.

The system mean value, M_s, is shown as the average value of D_i, and is always identical to the average value of I_j:

$$M_s = \sum_{i=1}^{N} D_i = \sum_{j=1}^{N} I_j \qquad \textbf{(8)}$$

The dominancy factor, D_i, can be compared to the system mean value, M_s, to decide if the main parameter A_{ii} is a dominant parameter or not. If D_i is found to be greater than M_s, then A_{ii} is considered a dominant parameter. If D_i is found to be smaller than M_s, then A_{ii} is considered a subordinate parameter. The interactivity factor, I_j, also can be used same manner to obtain the degree of interactivity of the main parameter A_{jj}. If I_j is found to be greater than M_s, then A_{jj} is considered an interactive parameter. If I_j is found to be smaller than M_s, then A_{jj} is considered an inert parameter. The mean value, Ms, can be calculated using any type of sample tendency statistic (e.g. median, harmonic mean, etc.) depending on the nature of the problem.

A_{11}	A_{12}	A_{13}	.	A_{1N}	D_1
A_{21}	A_{22}	A_{23}	.	A_{2N}	D_2
A_{31}	A_{32}	A_{33}	.	A_{3N}	D_3
.	.	.	.	.	.
A_{N1}	A_{N2}	A_{N3}	.	A_{NN}	D_N
I_1	I_2	I_3	.	I_N	M_s

Figure 8 - A generic N^2 Diagram showing main parameters, A_{ii}, as leading diagonal components, the interactions as off-diagonal components (A_{ij} where i,j = 1 to N), dominancy factor, D_i, interactivity factor, I_j, and the mean value for the system M_s.

5.1.3 Prioritization Example

An example of a fictitious HLW repository system consisting of five major parameters is shown in the 5^2-interaction matrix in Figure 9. The system shown in Figure 9 is designed to see how the near-field parameters surrounding the un-aged waste package are interacting with each other. The five main parameters are identified as:

- A_{11}=emplacement drift construction
- A_{22}=water flow, transport, and infiltration (hydrology)
- A_{33}=heat
- A_{44}=engineered barrier
- A_{55}=waste package

A_{11} Emplacement Drift Construction	Permeability increases near the drift wall (2)	Interfere with heat flow pattern (1)	Limit EB design (1)	Limit waste package design and emplacement method (2)	D_1=6
Impact on construction method (2)	A_{22} Flow Transport Infiltration	Alters convective heat transfer (4)	Degrade EB (chemistry change, saturation change) (3)	Increase degradation of the waste package (seepage, dripping, rock fall) (4)	D_2=13
Dictate repository design by thermal load (4)	Impact on flow pattern (dryout zone, condensation, buoyancy flow) (4)	A_{33} Heat	Alters mechanical and chemical behavior of EB (4)	Impact on canister material and structure (3)	D_3=15
Impact on drift design (3)	Impact on flow pattern (diver flow direction) (1)	Interfere thermal properties and processes (1)	A_{44} Engineered Barrier (EB)	Protect Waste Package degradation from rock fall and H2O (4)	D_4=9
Define construction method and design (3)	Source for radionuclides (4)	Source for heat (4)	Define EB design (4)	A_{55} Waste Package	D_5=15
I_1=12	I_2=11	I_3=10	I_4=12	I_5=13	M_s=11.6

Figure 9 - A 5 × 5-diagram describing a fictitious near-field HLW repository system. Shown are the main parameters, A_{ii}, as leading diagonal components, the interactions as off-diagonal components, dominancy factor, D_i, interactivity factor, I_j, and the mean value for the system M_s.

The numbers in parentheses in the off-diagonal terms refer to the fictitious ESQ rating assigned to the linking mechanisms. We find from the sum of the rows that hydrology (D_2 = 13), heat (D_3 = 15), and waste package (D_5 = 15) are the dominant parameters (> M_s = 11.6) influencing performance of the other parameters in the fictitious near-field HLW system. We also found that A_{11} (emplacement drift construction) has the least amount of influence (D_1 = 6) on the other main parameters. Unlike the widespread distribution of D_i values, interactivity factors, I_j, found from the sum of the columns, were in a narrow range ($13 \geq I_j \geq 10$). It appears that all main parameters are interacting with each other at the similar level.

The suggested N^2-impact matrix (or RES) approach can be applied for identifying and prioritizing key hydrological processes and parameters for the development of HLW repository in Japan. To do this, a hydrology system consisting of all the major hydrological parameters would be constructed and the hydrological processes linking the major parameters would be identified. A subjective but quantitative system such as the ESQ rating system will help to describe the degree of interaction between the main parameters.

5.2 Example Applications of the N^2-Impact Matrix in HLW Projects

This section will present several example applications of the N^2-Impact Matrix as applied to HLW programs. While most of the examples address issues at the near-field scale, the process and methods can be easily adapted to far-field issues at the PIA phase of development.

5.2.1 Identification of Coupled Thermal-Mechanical-Hydrological-Chemical Mechanisms

The response of the rock mass to HLW is a Thermal -Mechanical-Hydrological -Chemical (T-M-H-C) coupled phenomenon. The RES (Hudson, 1992) illustrated in Figure 10 was used to explain the coupled interactions of important factors affecting the rock mass surrounding the HLW repository (Lee et al., 2001). The matrix describes the major T-M-H-C components as the diagonal elements (A_{ij} where $i = j$) and the interactions between major components are represented as off-diagonal elements (A_{ij} where $i \neq j$). The system approach clearly identifies the impacts of *in situ* mechanical properties of the rock to the total system behavior of the rock in the repository. For example higher fracture normal stress (A_{22}) may impact the seepage of water into a drift (A_{33}) through the reduction of fracture aperture (A_{23}).

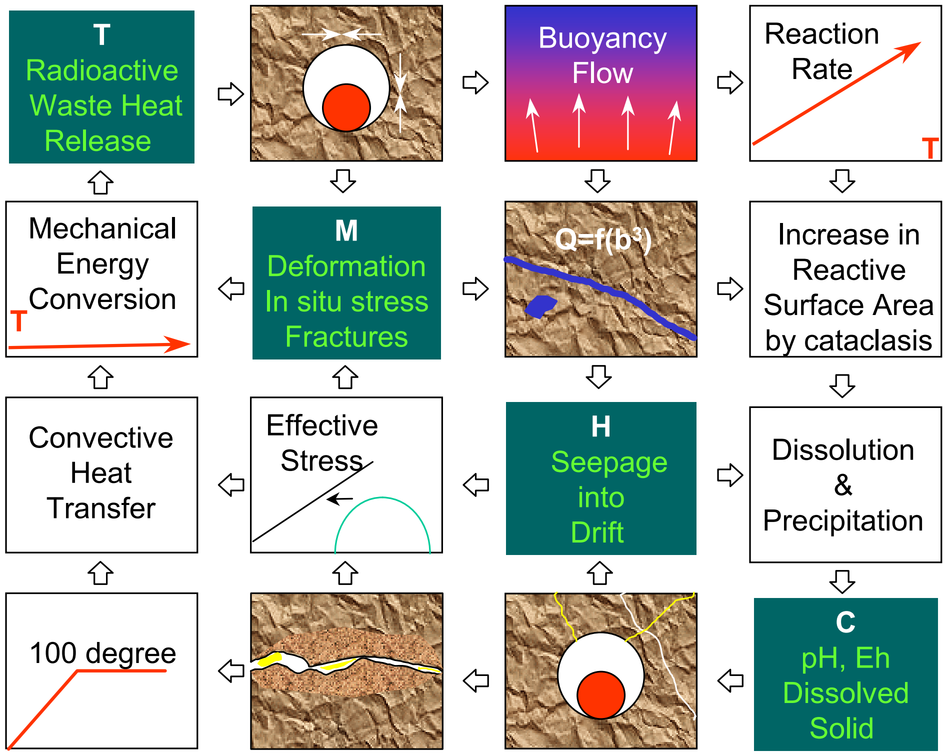

Figure 10 - The 4 × 4 Thermal-Mechanical-Hydrological-Chemical (T-M-H-C) coupled mechanism describing a HLW repository system (Lee et al., 2001).

5.2.2 Vertical Emplacement of the HLW Canisters with a Bentonite Buffer (Lee et al., 2002)

In a generic coupled Thermal-Hydrological-Mechanical (or T-H-M) study for a conceptual design of the HLW repository in the saturated granitic rock mass, the N^2 diagram was used to identify all the possible coupled-mechanisms between the three main parameters (T, H, and M). The identified coupled-mechanisms are then incorporated into the constitutive relations of the HLW package, buffer, back-filling, and rock mass (Figure 11). An impact matrix, shown in Figure 12 (bentonite buffer matrix) was constructed to identify the mechanisms needed to describe the coupled T-H-M mechanisms of the HLW waste package surrounded by the bentonite buffer in the fractured and saturated granitic rock mass (Lee et al., 2002).

The leading diagonal components were categorized as thermal (T), hydrological (H), and mechanical (M) parameters describing the performance of the near-field environment. The effects of chemistry (C) and interactions of T-H-M to C may be important factors to the near-field environment, but the scope of the study was limited only to the coupled T-H-M analysis. However, once the coupled T-H-M mechanism is understood, the chemistry component (C) and its interactions with other parameters can be added to the matrix. In the impact matrix (Figure 12) the sources for T, H, and M parameters and the contributing factors to the sources are listed in the diagonal positions. For example, the sources for the parameter T (temperature) are the decay heat from the spent fuel, geologic heat sources, and the conversion of mechanical deformation into heat. The temperatures in the bentonite buffer or in the surrounding rock are affected by the aging time of the spent fuel in the temporary storage, aerial density (spacing and size) of emplacement holes, and the use of the ventilation system in the storage room. The sources and the factors of each subject are listed to help us to understand the basics of the subject. However, the sources and the factors for the sources are not considered as part of the coupled relationships we are investigating.

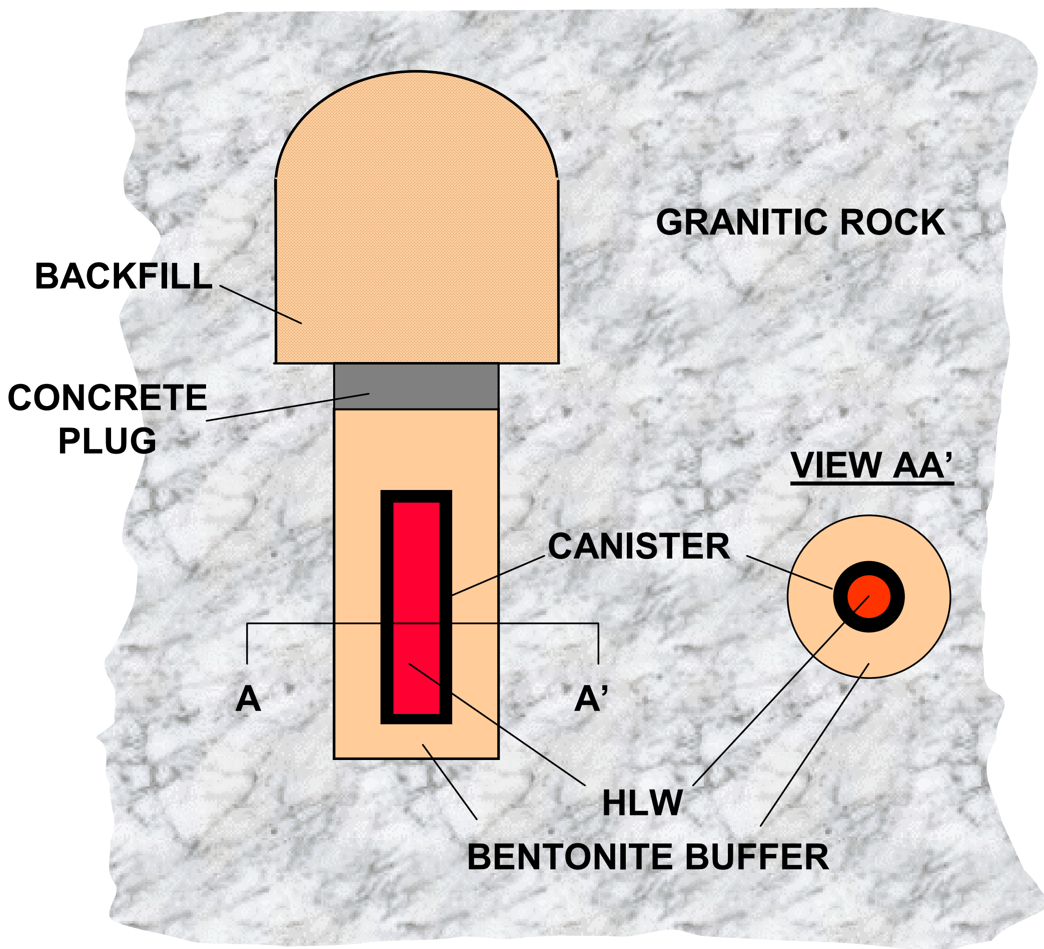

Figure 11 - Schematic diagram of the vertical emplacement of the HLW canister with a bentonite buffer in granitic rock (Lee et al., 2002).

In the impact matrix, each off-diagonal component, A_{ij}, describes the mechanism originating from A_{ii} and influencing the outcome of A_{jj}. For example, the A_{12} off-diagonal component of the rock matrix shown in Figure 12 describes the thermally induced mechanical behavior of the rock. To describe the mechanism, the thermal expansion coefficient of the rock and the temperature dependent elastic properties of the rock are needed.

<u>THERMAL</u> **Source** : decay heat, geologic heat source, mechanical deformation, chemical reaction **Factor** : aging (storage) time, aerial density (spacing, size) of emplacement holes, ventilation **Parameter** : temperature **Property** : thermal conductivity (bt), specific heat (bt), density (bt), geothermal gradient (rx), heat flux (rx)	**Mechanism** : heat pipe (convection, vaporization, condensation), vapor diffusion, water property change **Property** : temperature dependent hydrological properties (viscosity-fl, density-fl), vapor diffusivity (thermal, isothermal, molecular-bt), latent heat (fl)	**Mechanism** : thermal expansion, temperature dependent elasticity **Property** : thermal expansion coefficients (bt, fl), temperature dependent strength, E (bt) and ν (bt)
Mechanism : heat pipe (convection, vaporization, condensation), thermal property change **Property** : moisture dependent thermal conductivity (bt) and specific heat (bt)	**<u>HYDROLOGICAL</u>** **Source** : rain fall, ground water, moisture content **Factor** : climate, water table, topography, rock type, fracture distribution **Parameter** : saturation **Property** : viscosity (fl), liquid diffusivity (bt), permeability (bt), hydrostatic head, moisture content (bt), porosity (bt)	**Mechanism** : buffer swelling, effective stress, saturation dependent mechanical property change **Property** : suction pressure (bt), moisture dependent strength, E (bt) and ν (bt)
Mechanism : energy conversion (friction), compaction **Property** : stress dependent thermal conductivity (bt) and specific heat (bt)	**Mechanism** : compaction **Property** : Biot's constants, stress dependent permeability (bt), diffusivity (bt)	**<u>MECHANICAL</u>** **Source** : *in situ* stress (tectonic, lithostatic, seismic) **Factor** : geologic setting, depth, EDZ, construction sequence and method, opening geometry, bentonite brick dimension **Parameter** : stress, deformation **Property** : E (bt), ν (bt), density (bt), strength(bt), cohesion(bt), friction angle(bt), porosity (bt)

Figure 12 - Impact matrix for the bentonite buffer surrounding the vertically emplaced HLW canister (bt-bentonite; rx-rock; fl-fluid; E- Young's modulus; ν-Poisson's ratio) (Lee et al., 2002).

The impact matrix shown in Figure 12 was constructed to include any sources, factors, and mechanisms related to the coupled T-H-M processes in the near-field environment around the HLW packages. However, those matrices may contain elements that have trivial influences to the overall performance of the repository. For example, a contribution from the mechanical energy conversion to heat, identified as A_{13} in Figure 12, is minimal to the overall heat generated by the spent fuel.

5.2.3 Identification of the Required Activities from Conceptual Design to License Application (Sorenson et al., 2000)

The Total System approach used for this program began with the development of the N^2 diagrams shown in Figure 13 in which the two 5 × 5 diagrams intersect at the reference design. In the upper left corner is the 5 × 5 matrix that shows the near-term activities required as the program moves forward from the conceptual design to the reference design. In the lower right corner is the 5 × 5 matrix that shows the future activities required as the program moves forward from the reference design to the license application. Each 5 × 5 matrix consists of 20 one-way interaction terms between the major sequential activities. Major sequential program activities are shown along the diagonal of the two 5 × 5 matrices and are placed along a horizontal time line that shows the four developmental stages.

The first 5 × 5 matrix identifies the recommended near-term activities as those critical in the evolution of the conceptual repository design to the reference design. Early definition of the QA structure, the PA tools, and the fundamental engineering components are the building blocks needed for all downstream activities. The second 5 × 5 matrix shows how SPA, Total Systems Performance Assessment (TSPA), data collection, and model validation activities are interrelated and drive the repository program's evolution from the reference design to the license application. The two 5 × 5 diagrams converge at Stage 2. Stage 1 activities begin with a baseline conceptual design and essentially modify that design into the reference design (Stage 2). Stage 3 activities take that reference design and modify it until it becomes the system specified in the license application, which is Stage 4.

The major activities shown in Stage 1 (i.e., PA, programmatic, and engineering analysis activities) are parallel activities as are the major activities shown in Stage 3 (i.e., detailed SPA, TSPA, and data collection). The N^2 diagram illustrates; 1) the need to move forward toward developing the reference design, 2) the interrelationship of activities, 3) the impact of near-term activities on downstream activities, and 4) the priority of near-term activities.

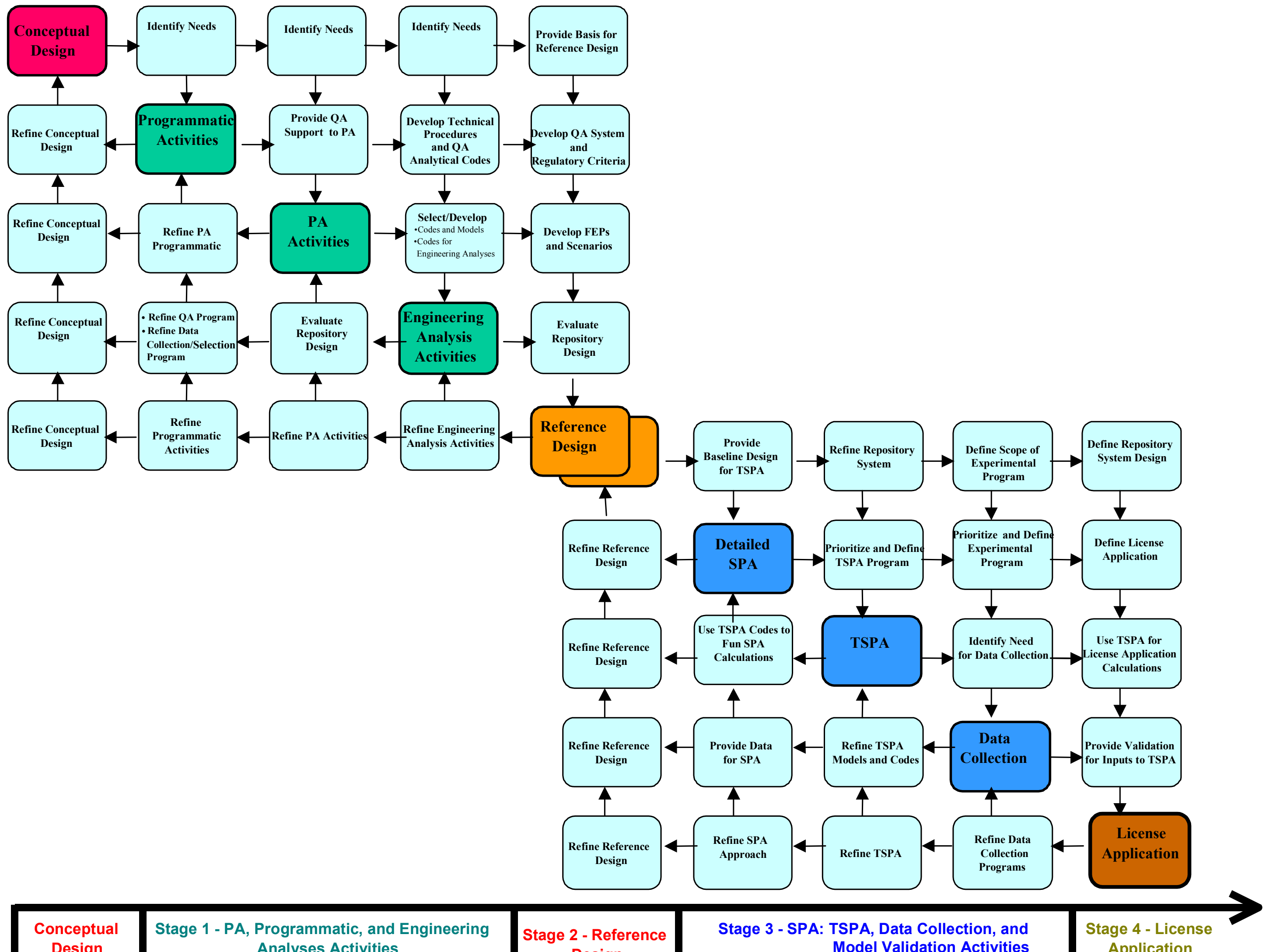

Figure 13 - Total System N-squared diagram used for identifying activities needed from conceptual design to license application (Sorenson et al., 2000).

6 Results of the Task 2 Hydrology Workshop

As stipulated in the statement of work, a key part of this project was to be the Hydrology Workshop. The intent of the Workshop was to convene a small group of domestic (to Japan) and international experts who are currently involved with NUMO to discuss the implications and importance of active tectonics on hydrology at the PI stage. The Workshop took place on March 23, 2006 at NUMO's headquarters in Tokyo, Japan and consisted of participants from the USA, Great Britain, and Japan.

The workshop was chaired to Thomas Lowry of Sandia National Laboratories (SNL) and consisted of two separate sessions; a technical program session that spanned the morning and early afternoon, and an open discussion session the filled the late afternoon.

6.1 The Technical Program

The technical program consisted of presentations by representatives of SNL, Lawrence Berkeley National Laboratory (LBL), NUMO, and the Central Research Institute of Electric Power Industry (CRIEPI). The presentations by SNL and LBL summarized their current work for NUMO and framed several discussion points that will be discussed below. The NUMO presentations addressed the status of current research and development (R&D) projects that are addressing hydrological issues in Japan and included summaries of work funded by NUMO, the Japan Atomic Energy Agency (JAEA), the National Institute of Advanced Industrial Science and Technology (AIST), the Radioactive Waste Management Funding and Research Center (RWMC), and the Institute of Research and Innovation (IRI). Several technical presentations by CRIEPI presented a thorough review of their efforts for the development of methods and tools to help characterize different hydrologic parameters and processes. Since most of this work is either ongoing or described is separate documents, it will not be detailed here.

6.2 The Discussion Session

The discussion session was built upon the information presented in the technical program and was designed to address four main objectives as follows:

- Identification of hydrological processes and parameters essential for PI
- Evaluation of R&D activities on hydrology in NUMO and other organizations
- Identification of issues and proposed R&D for solutions
- Recommendations on strategies for effective information dissemination

None of the objectives were specifically addressed in the form of a 'talking point' item, but rather, were addressed indirectly through the open discussions. From these discussions, and number of key points and common themes emerged. Those points and themes are listed below, with descriptive commentary given for each.

- Regarding the role of active tectonics on hydrology:
    - The international HLW programs outside of Japan do not address active tectonics at the PI stage with respect to regional scale hydrology.
    - Evidence points to the fact that this conceptualization may be applicable to Japan, but many questions remain unanswered and further investigation is needed.

- Japan could play a leading role in the organization and coordination of this type of research.

- Regarding initial site characterization (SC):
  - When beginning a SC process, it is important that the no conceptual model has been formed *a priori* so as to avoid data collection for the purpose of supporting the conceptual model.
  - For this reason, parameters cannot be prioritized prior to beginning the SC.
  - As data are collected, several conceptual models should be formed that honor the understandings gained from the data. As the level of understanding increases, conceptual models can be eliminated or reformed.

- Regarding the amount of data to collect:
  - The amount of data collected must be balanced by the ability to understand those data.
  - Ample time must be given between collection efforts to allow for a thorough analysis of each set of data.
  - Distinctions must be made between data collection and data understanding. Additionally, it must be made clear what level of understanding is needed at each stage of the SC process.
  - The understanding and analysis effort should include mechanisms for identifying those data, which if they were collected, would reduce the uncertainty of the assessment the most. This is an iterative process.
  - Geostatistics should be employed to guide data collection efforts that will maximize the amount of understanding of the site.

- Regarding data collection and analysis tools:
  - There most likely exist adequate data collection methods and analysis tools to do an accurate SC.
  - What is important is the interpretation of the data and the avoidance of fitting those data to pre-conceived conceptual models (see above).

- Regarding the SC process as a whole:
  - Effort should be made to avoid the process being driven by schedule rather than technical needs. Adequate time must be given to thoroughly analyze and understand the characterization at each stage of development. If this process moves ahead prior to adequate understanding, then difficulties may emerge.
  - It is important to link the SC process with the performance assessment (PA) process. The SC process should support the PA process and the PA process should guide the SC process. In this manner, the SC and PA will advance together through each stage of site development. Similarly, numerical models outside of PA should also be linked to the SC process.
  - SC should include the means to identify 'show-stoppers', those issues at the site that could eliminate that site from consideration (e.g. an active fault is found).
  - From the outset, an integrated, structured, and rational program should be defined, with provisions for updating and reforming this program as conditions dictate.

- Regarding public involvement:
  - Stakeholders need to feel as if they are part of the process from start to finish.
  - The appropriateness of the SC and PA is very important to convey to the public. However, this should be balanced by the need to satisfy the scientific requirements.
  - Information should be presented to the public that demonstrates adequate understanding of the site.
  - Information should not be filtered, but presented on a graduated basis from simple overviews to detailed analysis reports. What might be important for one set of stakeholders might not be important for a different set of stakeholders.
  - The public needs to be assured that the site selection process is reversible at any point in time meaning that if a 'show-stopper' is found, the site will be dropped as a potential repository site and alternatives will be sought.

It should be noted that the key points and themes presented above are listed in no particular order since no attempt was made during the Workshop to prioritize these items. The intent was to provide perspective and content to NUMO for fulfilling their own objective.

One paradigm that was revisited several times during the day was that of not seeing the forest for the trees. The meaning of this metaphor in the context of the Workshop is that at the PI stage, the interest lies in characterizing the forest, and not the individual trees. However, the importance of understanding the trees before one can describe the forest was also pointed out. This apparent conflict was rectified through the notion of a balanced approach to research, data collection, analysis, understanding, and modeling in that data collection must be guided by the level of current understanding and model uncertainties. This theme is repeated several times in the key points listed above.

Part of the discussion session also presented suggested areas for future R&D that would be applicable to NUMO's objective. These involved the development of new SC methods and tools, advancement of geostatistical applications, detailed flow and transport studies, and application of the N^2 Impact Matrix (discussed above in Section 6). Consensus among the group was that the suggested items were worthy of pursuit but that discussions of the details of each should be saved for a later date.

7 References

AECL, 1994. Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste. AECL-10711, Atomic Energy Canada, Ltd. (AECL).

AkEnd, 2002. Site Selection Procedure for Repository Sites: Recommendations of the AkEnd Committee on a Site Selection Procedure for Repository Sites, Arbeitskreis Auswahlverfahren Endlagerstandorte, Köln, Germany.

Alexander, W.R., Frieg, B., Ota, K. and Bossart, P., 1996a. NAGRA Bulletin 27. 27, NAGRA.

Alexander, W.R., McKinley, I.G., Frick, U. and Ota, K., 1996b. The Grimsel Field Tracer Migration Experiment - What Have We Achieved After a Decade of intensive Work, Field Tracer Experiments: Role in the Prediction of Radionuclide Migration. Proceedings of an NEA/EX GEOTRAP Workshop, Cologne, Germany, pp. 119-122.

Almén, K.-E. and Stenberg, L., 2005. Äspö Hard Rock Laboratory, Characterization methods and instruments, Experiences from the construction phase. Technical Report TR-05-11, SKB, Stockholm, Sweden.

Alonso, U. et al., 2006. Role of inorganic colloids generated in a high-level deep geological repository in the migration of radionuclides: Open questions. Journal of Iberian Geology, 32(1): 79-94.

ANDRA, 2001a. Dossier 2001 Argile: Synthesis Report – Part A, The National Agency for Radioactive Waste Management (ANDRA).

ANDRA, 2001b. Dossier 2001 Argile: Synthesis Report – Part B, The National Agency for Radioactive Waste Management (ANDRA).

ANDRA, 2005a. Dossier 2005 Argile: Synthesis Report, Evaluation of the feasibility of a geological repository, The National Agency for Radioactive Waste Management (ANDRA).

ANDRA, 2005b. Dossier 2005: ANDRA research on the geological disposal of high-level long-lived radioactive waste – Results and perspectives, The National Agency for Radioactive Waste Management (ANDRA).

Bäckblom, G. and Munier, R., 2002. Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results. Technical Report TR-02-24, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

Barton, C.A., Zoback, M.D. and Moos, D., 1995. FLUID-FLOW ALONG POTENTIALLY ACTIVE FAULTS IN CRYSTALLINE ROCK. Geology, 23(8): 683-686.

Billington, D.E., Lever, A.A. and Wisbey, S.J., 1990. Radiological Assessment of Deep Geological Disposal: Work for UK Nirex Limited, OECD-NEA, IAEA, CEC Symposium on Safety Assessment of Radioactive Waste Repositories, Paris, pp. 271-281.

Bossart, P., Hermanson, J. and Mazurek, M., 2001. Äspö Hard Rock Laboratory, Analysis of fracture networks based on the integration of structural and hydrogeological observations on different scales. Technical Report TR-01-21, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

Brown, A. et al., 1994. Geology of Lac du Bonnet Batholith, Manitoba. unpublished, Atomic Energy Canada, Ltd.

Brown, P.A., 2000. The Canadian Experience with Public Interveners on the Long-Term Management of Nuclear Fuel, Stakeholder Confidence and Radioactive Waste Disposal. Nuclear Energy Agency, Organization for Economic Co-Operation and Development (NEA/OECD), Paris, France, pp. 53-58.

BSC, 2004a. Saturated Zone Site-Scale Model. MDL-NBS-HS-000011, Rev. 02, S0045, Bechtel SAIC Company, LLC, Las Vegas, NV.

BSC, 2004b. Site-Scale Saturated Zone Transport. MDL-NBS-HS-000024, Rev. 00, S0025, Bechtel SAIC Company, LLC, Las Vegas, NV.

BSC, 2004c. Water-level data analysis for the saturated zone site-scale flow and transport model. ANL-NBS-HS-000034 REV 02, Bechtel SAIC Company, LLC, Las Vegas, NV.

BSC, 2004d. Yucca Mountain Site Description. TDR-CRW-GS-000001, Bechtel SAIC Company, LLC, Las Vegas, NV.

BSC, 2005. Features, events, and processes in SZ flow and transport. ANL-NBS-MD-000002 REV04C, Bechtel SAIC Company, LLC, Las Vegas, NV.

CEAA, 1998. Report of the Nuclear Fuel Waste Management and Disposal Concept Environmental Assessment Panel, Canadian Environmental Assessment Agency (CEAA).

Chandler, N.A., 2003. Twenty Years of Underground Research at Canada’s URL, Proc. WM ’03 Conference Tucson, AZ.

CoRWM, 2006a. Consolidated Scores Taken from the Specialist Workshops Scoring Report. 1499, Committee on Radioactive Waste Management, London.

CoRWM, 2006b. CoRWM's MCDA Scoring Process. 1497, Committee on Radioactive Waste Management, London.

CoRWM, 2006c. CoRWM Specialist Workshops – Scoring. CoRWM 1502, Catalyze Limited.

Courteaud, M., Ritz, M., Robineau, B., Join, K.L. and Courdray, J., 1997. New geological and hydrogeological implications of the resistivity distribution inferred from audiomagnetotellurics over La Fournaise young shield volcano (Reunion Island). Journal of Hydrology, 203: 93-100.

Curewitz, D. and Karson, J.A., 1997. Structural settings of hydrothermal outflow: Fracture permeability maintained by fault propagation and interaction. Journal of Volcanology and Geothermal Research, 79: 149-168.

Custodio, E., 1989. Groundwater Characteristics and Problems in Volcanic Rock Terrains: Isotope Techniques in the Study of the Hydrology of Fractured and Fissured Rocks. 329.2/6, International Atomic Energy Agency, Vienna.

Degueldre, C. and Favarger, P.Y., 2003. Colloid analysis by single particle inductevely coupled plasma-mass spectroscopy: a feasibility study. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 217: 137-142.

Deutsch, C.V. and Journel, A.G., 1992. GSLIB Geostatistical Software Library and User's Guide. Oxford University Press, New York, NY.

Edmunds, W.M. and Savage, D., 1991. Geochemical characteristics of groundwater in granites and related crystalline rocks. In: R.A. Downing and W.B. Wilkinson (Editors). Oxford University Press, pp. 266-282.

ENRESA, 1995. Almacenamiento Geológico Profundo de Residuos Radioactivos de Alta Actividad (AGP) Diseños Conceptuales Genréricos. ENRESA Report 11/95.

ENRESA, 1999a. Fifth General Radioactive Waste Plan. ENRESA 07/1999.

ENRESA, 1999b. Survey of the attitudes of the population to the Radioactive Waste Storage Centre of El Cabril, Hispania Services.

ENRESA, 2004. Plan de I+D 2004-2008. ENRESA 01/2004.

ENRESA, 2006. ENRESA Web Site, www.enresa.es.

EPRI, 1989. Probabilistic Seismic Hazard Evaluations at Nuclear Plant Sites in the Central and Eastern United States: Resolution of the Charleston Earthquake Issue. EPRI NP 6395D, Electric Power Research Institute, Palo Alto, CA.

Erickson, J.R. and Waddell, R.K., 1985. Identifications and Characterization of Hydrologic Properties of Fractured Tuff Using Hydraulic and Tracer Tests - Test Well USW H-4, Yucca Mountain, Nye County, Nevada. 85-4066, USGS, Denver, CO.

Escuder-Viruete, J., Carbonell, R., Jurado, M.J., Martí, D. and Pérez-Estaún, A., 2001. Two-dimensional geostatistical modeling and prediction of the fracture system in the Albalá Granitic Pluton, SW Iberian Variscan Massif, Spain. Journal of Structural Geology, 23: 2011-2023.

Escuder-Viruete, J., Carbonell, R., Martí, D. and Pérez-Estaún, A., 2003a. 3-D stochastic modeling and simulation of fault zones in the Albalá Granitic Pluton, SW Iberian Variscan Massif. Journal of Structural Geology, 25: 1487-1506.

Escuder-Viruete, J., Carbonell, R., Martí, D. and Pérez-Estaún, A., 2003b. Architecture of fault zones determined from outcrop, cores, 3-D seismic tomography and geostatistical modeling: example from the Alabalá Granitic Pluton, SW Iberian Variscan Massif. Tectonophysics, 361: 97-420.

Escuder-Viruete, J., Carbonell, R., Pérez-Soba, C., Martí, D. and Pérez-Estaún, A., 2004. Geological, geophysical and geochemical structure of a fault zone developed in granitic rocks: Implications for fault zone modeling in 3-D. International Journal of Earth Sciences, 93(2): 172-188.

Fairley, J.P., Heffner, J. and Hinds, J.J., 2003. Geostatistical evaluation of permeability in an active fault zone. Geophysical Research Letters, 30(18): doi:10.1029/2003GL018064.

Fetter, C.W., 1999. Contaminant Hydrogeology. Prentice-Hall Inc., Upper Saddle River, New Jersey.

Folio, J.L., 2001. Modélisation numérique des circulations d'eau souterraine dans le massif de la Fournaise. Université de la Réunion, 150 pp.

Freeze, A.R. and Cherry, J.A., 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 604 pp.

Fridrich, C.J., Dudley, W.W., Jr. and Stuckless, J.S., 1994. Hydrogeologic Analysis of the Saturated-Zone Ground-Water System, Under Yucca Mountain, Nevada. Journal of Hydrology, 154: 133-168.

Gascoyne, M., 2004. Hydrogeochemistry, groundwater ages and sources of salts in a granitic batholith on the Canadian Shield, southeastern Manitoba. Applied Geochemistry, 19: 519-560.

Gascoyne, M. and Kamineni, D.C., 1994. The hydrogeochemistry of fractured plutonic rocks in the Canadian Shield. Applied Hydrogeology, 2: 43-49.

Ge, S. and Cheree Stover, S., 2000. Hydrodynamic response to strike- and dip-slip faulting in a half-space. Journal of Geophysical Research, 105(B11): 25513-25524.

Geckeis, H., Ngo Mahn, T., Bouby, M. and Kim, J.I., 2003. Aquatic colloids relevant to radionuclide migration: characterization by size fractionation and ICP-mass spectrometric detection. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 217: 101-108.

Gelhar, L.W., 1993. Stochastic Subsurface Hydrology. Prentice-Hall Inc., Englewood Cliffs, New Jersey, 390 pp.

Gillespie, P.A., Howard, C.B., Walsh, J.J. and Wartterson, J., 1993. Measurement and characterization of spatial distributions of fractures. Tectonophysics, 226: 113-141.

Gimbert, L.J., Andrew, K.N., Haygarth, P.M. and Worsfold, P.J., 2003. Environmental applications of flow field-flow fractionation (FIFFF). Trends in Analytical Chemistry, 22(10): 615-633.

Gómez-Hernández, J.J. and Srivastava, R.M., 1989. ISIM3D: an ANSI-C three-dimensional multiple indicator conditional simulation program. Computer and Geosciences, 16: 395-440.

Gómez, P., Garralón, A. and Turrero, M.J., 2001. Redox modeling of the waters in a restored uranium mine in Spain. Water Rock Interaction, 2: 1237-1240.

Gómez, P. et al., 2006. Hydrogeochemical characteristics of deep groundwaters of the Hesperian Massif (Spain). Journal of Iberian Geology, 32(1): 113-131.

Grecksch, G., Roth, F. and Kümpel, H.-J., 1999. Coseismic well-level changes due to the 1992 Roermond earthquake compared to static deformation of half-space solutions. International Journal of Geophysics, 138: 470-478.

Gudmundsson, A., 2000. Active fault zones and groundwater flow. Geophysical Research Letters, 27(18): 2993-2996.

Hantush, M.S., 1966. Analysis of Data from Pumping Tests in Anisotropic Aquifers. Journal of Geophysical Research, 71(2): 421-426.

Hauser, W., Geckeis, H., Kim, J.I. and Fierz, T., 2002. A mobile laser-induced breakdown detection system and its application for the in-situ monitoring of colloid migration. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 203: 37-45.

Hauser, W., Götz, R., Geckeis, H. and Kienzler, B., 2003. In-situ colloid detection in granite groundwater along the Äspö hard rock laboratory access tunnel, Swedish Nuclear Fuel and Waste Management Co. (SKB).

Hinkkanen, H., ÖhBerg, A., Ikonen, A., Heikkinen, E. and Helenius, J., 1996. Investigation Methods and Equipment Used in the Detailed Site Investigations 1993-1996, Summary Report. Posiva Work Report PATU-96-84., Posiva Oy, Helsinki, Finland.

Hodgkinson, D. and Black, J., 2005. Äspö Task Force on modeling of groundwater flow and transport of solutes, review of Tasks 6A, 6B, and 6B2. Technical Report TR-05-14, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

Hora, S.C. and Iman, R.L., 1989. Expert Opinion in Risk Analysis: The NUREG 1150 Methodology. Nuclear Science and Engineering, 102(4): 323-331.

Hora, S.C., von Winterfledt, D. and Trauth, K., 1991. Expert Judgment on Human Intrusion into the Waste Isolation Pilot Plant. SAND90-3063, Sandia National Laboratories, Albuquerque, NM.

Huang, F.-q. et al., 2004. Response changes of some wells in the mainland subsurface fluid monitoring network of China, due to the September 21, 1999, Ms7.6 Chi-Chi Earthquake. Tectonophysics, 390: 217-234.

Hudson, J.A., 1992. Rock Engineering Systems, Theory and Practice. Oxford University Press, New York, NY, London, 185 pp.

IAEA, 2002. Institutional framework for long term management of high level waste and/or spent nuclear fuel. TECDOC-1323, International Atomic Energy Association.

INLA, 1999. The role of the public and administrative mechanisms of public involvement in the development of a final disposal solution for radioactive waste in Spain. Report to Working Group #5., International Nuclear Law Association (INLA).

Iverson, R.M., 1995. Can magma-injection and groundwater forces cause massive landslides o Hawaiian volcanoes? Journal of Volcanology and Geothermal Research, 66: 295-308.

Iwatsuki, T. and Yoshida, H., 1999. Groundwater chemistry and fracture mineralogy in the basement granitic rock in the Tono uranium mine area, Gifu Prefecture, Japan - Groundwater composition, Eh evolution analysis by fracture filling minerals. Geochemical Journal, 33: 19-32.

JNC, 2000. Project Overview Report. JNC TN1410 2000-001, Japan Nuclear Cycle Development Institute (JNC).

Join, J.L., Folio, J.L. and Robineau, B., 2005. Aquifer and groundwater within active volcano shield volcanoes; evolution of conceptual models in the Piton de la Fournaise Volcano. Journal of Volcanology and Geothermal Research, 147(1-2): 187-201.

Karasaki, K. et al., 2005. Feature Detection, Characterization and Confirmation Methodology: Interim Progress Report, Lawrence Berkeley National Laboratory.

Kersting, A.B. et al., 1999. Migration of Plutonium in Ground Water at the Nevada Test Site. Nature, 397(6714): 56-59.

Kersting, A.P. and Reimus, P.W., 2003. Colloid-Facilitated Transport of Low-Solubility Radionuclides: A Field, Experimental and Modeling Investigation. UCRL-ID-149688, Lawrence Livermore National Laboratory, Livermore, CA.

Keusen, H.R., Ganguin, J., Schuler, P. and Buletti, M., 1989. Grimsel Test Site: Geology. 87-14E, GEOTEST, Bern, Switzerland.

King, C.-Y. et al., 1999. Earthquake-related water-level changes at 16 closely clustered wells in Tono, central Japan. Journal of Geophysical Research, 104(B6): 13073-13082.

King, F., 2002. Recent Developments in Nuclear Waste Management in Canada, Tucson, AZ.

Kitagawa, Y. and Koizumi, N., 2000. A study on the mechanism of coseismic groundwater changes: Interpretation by a groundwater model composed of multiple aquifers with different strain responses. Journal of Geophysical Research, 105(B8): 19121-19134.

Kurosawa, S., James, S.C., Yui, M. and Ibaraki, M., 2006. Model analysis of the Colloid and Radionuclide Retardation experiment at the Grimsel Test Site. Journal of Colloid and Interface Science, in press.

Laaksoharju, M., 1999. Groundwater characterisation and modelling: problems, facts, and possibilities. Technical Report TR-99-42, SKB, Stockholm.

Lallo, I. and Hellä, P.D., 1997. Updating the TUTKA data-management system (in Finnish with an English abstract). Working Report 97-04, Posiva Oy, Helsinki, Finland.

LBNL, 1996. Geological Problems in Radioactive Waste Isolation. Second Worldwide Review. LBNL-38915, UC814, Earth Sciences Division. Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA.

LBNL, 2001. Geological Problems in Radioactive Waste Isolation. Third Worldwide Review, Earth Sciences Division. Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA.

Lee, M.Y., George, J.T. and Schelling, J.F., 2001. Measurements of in situ stress and deformability of the rock in the Exploratory Studies Facility, Yucca Mountain, Nevada, Published in Proc. of Rock Engineering for Underground Waste Isolation, Proc. of Rock Engineering for Underground Waste Isolation. Korean Society for Rock Mechanics & Korea Nuclear Society, Seoul, Korea.

Lee, M.Y. et al., 2002. Coupled Thermal-Hydrological-Mechanical Modeling For The Development Of The Underground High Level Nuclear Waste Repository In The Republic Of Korea, Sandia National Laboratories, Albuquerque, NM.

Lenat, J.F., Fitterman, D., Jackson, D.B. and Labazuy, P., 2000. Geoelectrical structure of the central zone of Piton de la Fournaise volcano (Reunion). Bulletin of Volcanology, 62(2): 75-89.

Léonardi, V., Arthaud, F., Tovmassian, A. and Karakhanin, A., 1998. Tectonic and seismic conditions for changes in spring discharge along the Garni right lateral strike slip fault (Armenian Upland). Geodinamica Acta, 11(2-3): 85-103.

Lidskog, R. and Andersson, A.-C., 2002. The management of radioactive waste. A description of ten countries. 91-973987-3-X, Örebro University.

Lindskog, R. and Andersson, A.-C., 2002. The Management of Radioactive Waste: A Description of Ten Countries, Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden.

Liu, J., Elsworth, D., Brady, B.H. and Muhlhaus, H.B., 2000. Strain-dependent Fluid Flow Defined Through Rock Mass Classification Schemes. Rock Mechanics and Rock Engineering, 33(2): 75-92.

Luckey, R.R. et al., 1996. Status of Understanding of the Saturated-Zone Ground-Water Flow System at Yucca Mountain, Nevada, as of 1995: Quality Assurance Requirements and Description. 96-4077, DOE/RW-0333P, Rev. 16, USGS

U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Denver

Washington, D.C.

Lund, B., 2005. Effects of deglaciation on the crustal stress field and implications for endglacial faulting: A parametric study of simple Earth and ice models. Technical Report TR-05-04, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

Maloszewski, P. and Zuber, A., 1985. On the theory of tracer experiments in fissured rocks with a porous matrix. Journal of Hydrology, 79: 333-358.

Markova, R., 2003. Investigations on clays for radioactive waste disposal. Geology and Geophysics, 46(1): 379-384.

Martin, C.D. and Kaiser, P.K., 1996. Mine-by Experiment Committee Report, Phase I: Excavation response Summary and Implications. AECL-11382, Atomic Energy Canada, Ltd.

Mastin, L.G., 1997. Evidence for water influx from a caldera lake during the explosive hydromagmatic eruption of 1790, Kilauea volcano, Hawaii. Journal of Geophysical Research, 102(B9): 20093-20109.

McCombie, C., 2003. Status of Geological Repositories for Used Nuclear Fuel. Background Papers, series 6: Technical Methods, Paper 6-3 National Waste Management Organization (NWMO).

McEwen, T. and Äikäs, T., 2000. The site selection process for a spent fuel repository in Finland – Summary report. Report 2000-15, Posiva Oy, Helsinki, Finland.

Milnes, A.G., 2002. Swedish deep repository siting programme. Technical Report TR-02-18, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

Milnes, A.G., Gee, D.G. and Lund, C.E., 1998. Crustal Structure and Regional Tectonics of SE Sweden and the Baltic Sea. Technical Report TR-98-21, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

Missana, T. and Geckeis, H., 2004. The CRR final project series: 2. Results of the supporting laboratory programme. Technical Report NTB 03-02, NAGRA.

Moench, A.F., 1989. Convergent Radial Dispersion: A Laplace Transform Solution for Aquifer Tracer Testing. Water Resource Research, 25(3): 439-447.

Moench, A.F., 1995. Convergent Radial Dispersion in a Double-Porosity Aquifer with Fracture Skin: Analytical Solution and Application to a Field Experiment in Fractured Chalk. Water Resource Research, 31(8): 1823-1835.

Muir-Wood, R. and King, G.C.P., 1993. Hydrological signature of earthquake strain. Journal of Geophysical Research, 98: 22035-22068.

Munier, R., 1995. Studies of geological structures at Äspö. Comprehensive summary of results. SKB Preliminary Report PR-25-95-21, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

Munier, R. and Hökmark, H., 2004. Respect distances. Rationale and means of computation. Report R-04-17, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

Murphy, B.L. and Kuhn, R.G., 2002. Setting the Terms of Reference in Environmental Assessments: Canadian Nuclear Fuel Waste Management. Canadian Public Policy, XXVII(3): 249-266.

NEA, 2005. The control of safety of radioactive waste management in France, Nuclear Energy Agency (NEA).

NEA/OECD, 2003a. The French R&D Programme on Deep Geological Disposal of Radioactive Waste: An International Peer Review of the 'Dossier 2001 Argile', Nuclear Energy Agency / Organisation for Economic Co-operation and Development (NEA/OECD), Paris, France.

NEA/OECD, 2003b. SAFIR 2: Belgian R&D Programme on the Deep Disposal of High-level and Long-lived Radioactive Waste, An International Peer Review, Nuclear Energy Agency / Organisation for Economic Co-operation and Development (NEA/OECD), Paris, France.

Neuman, S.P., 1975. Analysis of Pumping Test Data from Anisotropic Unconfined Aquifers Considering Delayed Gravity Response. Water Resources Research, 11(2): 329-342.

NUMO, 2002a. Open Solicitation for Candidate Sites for Safe Disposal of High-Level Radioactive Waste, Nuclear Waste Management Organization of Japan (NUMO).

NUMO, 2002b. Repository Concepts, Nuclear Waste Management Organization of Japan (NUMO).

NUMO, 2002c. Siting Factors for the Selection of Preliminary Investigation Areas, Nuclear Waste Management Organization of Japan (NUMO).

NUMO, 2004. Evaluating Site Suitability for a HLW Repository, Scientific Background and Practical Application of NUMO's Siting Factors. NUMO-TR-04-04, Nuclear Waste Management Organization of Japan.

NWMO, 2005a. Choosing a Way Forward: The Future Management of Canada's Used Nuclear Fuel; Final Study, National Waste Management Organization (NWMO).

NWMO, 2005b. Incorporation of Seaborn Panel Recommendations and Insights in the Work of the NWMO. Background Papers, Series 2: Social and Ethical Dimensions, Paper 2-8, National Waste Management Organization (NWMO).

NWMO, 2006. NWMO Website: http://www.nwmo.ca/default.aspx?l=English.

O'Brien, G., 1988. Milestone SPH40NM4 (Level 4) - Memo to TPO: Possible Perched-Water Occurrences North of Yucca Mountain, Memorandum from G. O'Brien (USGS) to R. Craig (USGS), September 28, 1998, with attachment, 'Perched-Water Analysis Death Valley Region.' ACC: MOL.19981130.0221; MOL.19990113.0213.

O'Brien, G.M., 1992. Earthquake-induced water-level fluctuations at Yucca Mountain, Nevada. Open File Report: 93-173, U.S. Geological Survey.

OCRWM, 2006. Office of Civilian Radioactive Waste Management website: http://www.ocrwm.doe.gov/index.shtml.

Ohta, M.M. and Chandler, N.A., 1997. AECL's Underground Research Laboratory: Technical Achievements and Lessons Learned. AECL-11760, Atomic Energy Canada, Ltd.

Ondraf/Niras, 2001. SAFIR 2: Safety Assessment and Feasibility Interim Report 2. NIROND 2001-06 E, Belgian National Agency for Radioactive Waste and Enriched Fissile Materials.

OPG, 2006. Ontario Power Generation website: http://www.opg.com/default3.asp.

Ophori, D.U. et al., 1996. Revised Model of Regional Groundwater Flow in the Whiteshell Research Area. AECL-11435, Atomic Energy Canada, Ltd. (AECL).

Paulamäki, S., Paananen, M. and Elo, S., 2002. Structure and geological evolution of the bedrock at southern Satakunta, SW Finland. Report 2002-04, Posiva Oy, Helsinki, Finland.

Penrose, W.R., Polzer, W.L., Essington, E.H., Nelson, D.M. and Orlandini, K.A., 1990. Mobility of Plutonium and Americium Through a Shallow Aquifer in a Semiarid Region. Environmental Science and Technology, 24: 228-234.

Pérez del Villar, L. et al., 2002. The uranium ore from Mina Fe (Salamanca, Spain) as a natural analogue of processes in a spent fuel repository. Chemical Geology, 190(1-4): 395-415.

Pérez del Villar, L. et al., 2003. Argillization processes at the El Berrocal analogue granitic system (Spain): mineralogy, isotopic study and implications for the performance assessment of radwaste geological disposal. Chemical Geology, 193(3-4): 273-293.

Pitkänen, P., Partamies, S. and Luukkonen, A., 2004. Hydrogeochemical interpretation of baseline groundwater conditions at theOlkiluoto site. Report 2003-07, Posiva Oy, Eurajoki, Finland.

Pöllänen, J. and Rouhiainen, P., 2002. Difference flow and electric conductivity measurements at the Olkiluoto site in Eurajoki, extended part of borehole KR15. Working Report 2002-43, Posiva Oy, Oikiluoto, Finland.

Posiva Oy, 2003a. Baseline Conditions at Olkiluoto. Report 2003-02, Posiva Oy, Helsinki, Finland.

Posiva Oy, 2003b. Onkalo Underground Characterisation and Research Programme (UCRP). Report 2003-03, Posiva Oy, Helsinki, Finland.

Posiva Oy, 2005. Olkiluoto Site Description. Report 2005-03, Posiva Oy, Helsinki, Finland.

Posiva Oy, 2006. Posiva Oy Website: www.posiva.fi.

Quattrocchi, F. et al., 2000. Geochemical changes at the Bagni di Triponzo thermal spring during the Umbria-Marche 1997-1998 seismic sequence. Journal of Seismology, 4: 567-587.

Quilty, E.G. and Roeloffs, E.A., 1997. Water-level changes in response to the 20 December 1994 earthquake near Parkfield, California. American Seismological Society Bulletin, 87(2): 310-317.

Roeloffs, E.A. et al., 1995. Hydrologic effects of the June 28, 1992, Landers, California earthquake. Open File Report: 95-42, U.S. Geological Survey.

Rojstaczer, S. and Wolf, S., 1992. Permeability changes associated with large earthquakes: An example from Loma Prieta, California. Geology, 20: 211-214.

Rouhiainen, P., 1997. Groundwater flow measurements at the Olkiluoto site in Eurajoki, borehole KR10. Working Report PATU-96-83E, Posiva Oy, Helsinki, Finland.

Rouhiainen, P., 2000. Electrical Conductivity and Detailed Flow Logging at the Olkiluoto Site in Eurajoki, Boreholes KR1-KR11. Working Report 99-72, Posiva Oy, Helsinki, Finland.

Royal Society, 2006. The long-term management of radioactive waste: the work of the Committee on Radioactive Waste Management (CoRWM). Policy document 01/06, Royal Society.

Ruotsalainen, P., Alhonmäki-Aalonen, S., Aalto, T., Helenius, J. and Sellge, R., 1996. Development of the pressurized groundwater sampling equipment PAVE (in Finnish with an English abstract). Working Report PATU-96-82, Posiva Oy, Helsinki, Finland.

Satake, H., Murata, M. and Hayashi, H., 2003. Chemical characteristics of groundwater around the Mozumi-Sukenobu fault and the implication for fault activity. Geophysical Research Letters, 30(7): 1356, doi:10.1029/2002GL015239.

Sibson, R.H., 1981. Fluid flow accompanying faulting: field evidence and model. In: D.W. Simpson and P.G. Richards (Editors), Earthquake Prediction. American Geophysical Maurice Ewing Series, pp. 593-603.

SKB, 2001. Feasibility Studies – Östhammar, Nyköping, Oskarshamm, Tierp, Hultsfred, and Ävkarleby. Summary Report. SKB Technical Report TR-01-16, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

SKB, 2004a. Preliminary site description of the Forsmark area (version 1.1). Report R-04-15, SKB, Stockholm, Sweden.

SKB, 2004b. RD&D-Programme 2004: Programme for Research, Development and Demonstration of Methods for the Management and Disposal of Nuclear Waste, Including Social-Science Research. SKB Technical Report TR-04-21, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

SKB, 2005a. Preliminary safety evaluation for the Forsmark area, Based on data and site descriptions after the initial site investigation stage. SKB Technical Report TR-05-16, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

SKB, 2005b. Preliminary safety evaluation for the Simpevarp subarea, Based on data and site descriptions after the initial site investigation stage. SKB Technical Report TR-05-12, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

SKB, 2005c. Preliminary site description, Forsmark area – version 1.2. SKB Report R-05-18, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

SKB, 2005d. Preliminary site description, Simpevarp subarea – version 1.2. SKB Report R-05-08, Svensk Kärnbränlehantering AB, Stockholm, Sweden.

SKB, 2006. SKB Website: http://www.skb.se/default____8563.aspx.

SKB Website: http://www.skb.se/default____8563.aspx.

Smith, P.A. et al., 2001. The NAGRA-JNC in situ study of safety relevant radionuclide retardation in fractured crystalline rock I: Radionuclide Migration Experiment - Overview 1990-1996. 00-09, NAGRA, Wettengen.

Sorenson, K. et al., 2000. Preliminary Conceptual Design and Performance Assessment of a Deep Geological Repository for High-Level Waste in the Republic of Korea, Sandia National Laboratories, Albuquerque, NM.

Stanchell, F.W., Davison, C.C., Melnyk, T.W., Scheier, N.W. and Chan, T., 1996. The Disposal of Canada's Nuclear Fuel Waste: A Study of Postclosure Safety of In-Room Emplacement of Used CANDU Fuel in Copper Containers in Permeable Plutonic Rock, Volume 3: Geosphere Model. AECL-11494-3, Atomic Energy Canada, Ltd. (AECL).

Stanley, A. and Kuhn, R.G., 2003. Nuclear Waste and First Nations in Canada: An Evaluation of Canada's Nuclear Fuel Waste Management Discourse, International High Level Radioactive Waste Management Conference, Las Vegas, NV, pp. 1173-1178.

Stephansson, O. and Hudson, J.A., 1993. SKI/SKB FEPs identification and characterization via the 'Rock Engineering Systems' approach. SKB Arbetsrapport 93-36, SKB, Stockholm, Sweden.

Stevenson, D.R. et al., 1996a. Revised Conceptual Hydrogeologic Model of a Crystalline Rock Environment, Whiteshell Research Area, Southeastern Manitoba, Canada. AECL-11331, Atomic Energy Canada, Ltd. (AECL).

Stevenson, D.R., Kozak, E.T., Davison, C.C., Gascoyne, M. and Broadfoot, R.A., 1996b. Hydrologic Characteristics of Domains of Sparsely Fractured Rock in the Granitic Lac du Bonnet Batholith, Southeastern Manitoba, Canada. AECL-11558, Atomic Energy Canada, Ltd. (AECL).

Stone, W.J., 1999. Hydrogeology in Practice: A Guide to Characterizing Ground-Water Systems. Prentice Hall, Upper Saddle River, New Jersey, 248 pp.

Streltsova-Adams, T.D., 1978. Advances in Hydroscience. Well Hydraulics in Heterogeneous Aquifer Formations, 11. Academic Press, New York, New York, 357-423 pp.

Stuckless, J.S. and Dudley, W.W., 2002. The geohydrologic setting of Yucca Mountain, Nevada. Applied Geochemistry, 17(6): 659-682.

STUK, 2006. Radiation and Nuclear Safety Authority website: www.stuk.fi.

Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. Transactions of the American Geophysical Union: 519-524.

Tokunaga, T., 1999. Modeling of earthquake-induced hydrological changes and possible permeability enhancement due to the 17 January 1995 Kobe Earthquake, Japan. Journal of Hydrology, 223(3-4): 21-229.

Tröger, U., Dussel, M., Moeck, I. and Schandelmeier, H., 2001. A new approach to the reconnaissance of groundwater flow in hard rocks: Hydrotectonic. In: S.a. Wohnlich (Editor), New Approaches Characterizing Groundwater Flow. Swets & Zeitlinger Lisse.

USGS, 2001. Water-level data analysis for the saturated zone site-scale flow and transport model. ANL-NBS-HS-000034 REV 00 ICN 01, USGS, Denver.

USGS, 2002a. Software Code: MOENCH.vi, Function(2). V 1.0. PC, Windows 2000/NT 4.0/98. 10582-1.0-00.

USGS, 2002b. Software Code: rcv2amos.exe and MOENCH.vi, Function(1). V 1.0. PC, Windows 2000/NT 4.0/98. 10583-1.0-00.

USGS, 2004. Water-level data analysis for the saturated zone site-scale flow and transport model. ANL-NBS-HS-000034 REV 01 with errata, USGS, Denver.

van den Berg, R.J. and Damveld, H., 2000. Discussions on Nuclear Waste: A Survey on Public Participation, Decision-Making, and Discussions in Eight Countries, Laka Foundation, Amsterdam, Netherlands.

Vieno, T. and Ikonen, A.T.K., 2005. Plan for Safety Case of Spent Fuel Repository at Olkiluoto. Report 2001-01, Posiva Oy, Olkiluoto, Finland.

Vieno, T. and Nordman, H., 1999. Safety Assessment of Spent Fuel Disposal in Hästholmen, Kivetty, Olkiluoto, and Romuvaara: TILA-99. Posiva 99-07, Posiva Oy, Helsinki, Finland.

Volckaert, G., Bernier, F., Demarche, M. and Lalieux, P., 2004. The construction and the experimental programme of the URF HADES at Mol, Belgium. TN5400 2004-005, Japan Nuclear Cycle Development Institute.

Waddell, R.K., Robison, J.H. and Blankennagel, R.K., 1984. Hydrology of Yucca Mountain and Vicinity, Nevada-California - Investigative Results Through Mid-1983. 84-4267, USGS, Denver, CO.

Walther, C., Bitea, C., Hauser, W., Kim, J.I. and Scherbaum, F.J., 2002. Laser induced breakdown detection for the assessment of colloid mediated radionuclide migration. Nuclear Instruments and Methods in Physics Research B, 195: 374-388.

Wang, J.-A. and Park, H.D., 2002. Fluid permeability of sedimentary rocks in a complete stress-strain process. Engineering geology, 63: 291-300.

Windberg, A. et al., 2000. Äspö Hard Rock Laboratory: Final report of the first stage of the tracer retention understanding experiments. Svensk Kärnbränlehantering AB, Stockholm, Sweden.

Yoshida, H. et al., 2000. Overview of the stability and barrier functions of the granitic geosphere at the Kamaishi Mine: Relevance to radioactive waste disposal in Japan. Engineering geology, 56(1-2): 151-162.

Yoshida, H. and Takeuchi, M., 2004. An analogue of long-term stability of flow-path structure in crystalline rocks distributed in the orogenic belt, Japan. International journal of nuclear energy science and technology, 1(1): 116-24.

Yoshida, H., Takeuchi, M. and Metcalfe, R., 2005. Long-term stability of flow-path structure in crystalline rocks distributed in an orogenic belt, Japan. Engineering geology, 78(3-4): 275-284.

Zhang, X., Sanderson, D.J. and Barker, A.J., 2002. Numerical study of fluid flow of deforming fractured rocks using dual permeability model. International Journal of Geophysics, 151: 452-468.

Distribution

SANDIA INTERNAL:

4	MS 0735	T.S. Lowry, 06115
1	MS 0735	S.A. McKenna, 06115
1	MS 0735	S.J. Altman, 06115
1	MS 0751	G.L. Gettemy, 06117
1	MS 0751	R.P. Jensen, 06117
1	MS 0751	A.R. Lappin, 06117
1	MS 0751	M.Y. Lee, 06117
1	MS 0751	D.K. Meier, 06117
1	MS 0778	B.W. Arnold, 06851
1	MS 9409	S.C. James, 08757
2	MS 9018	Central Technical Files, 8944
2	MS 0899	Technical Library, 4536