

# CHEMICAL MODELING OF CEMENTITIOUS GROUT MATERIALS ALTERATION IN HLW REPOSITORIES

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## ABSTRACT

An investigation has been initiated into the nature of the chemical alteration of cementitious grout in HLW repository seals, and the implications for long-term seal performance. The equilibrium chemical reaction of two simplified portland cement-based grout models with natural Canadian Shield groundwater compositions was modeled with the computer codes PHREEQE and EQ3NR/EQ6. Increases in porosity and permeability of the grout resulting from dissolution of grout phases and precipitation of secondary phases were estimated. Two bounding hydrologic scenarios were evaluated, one approximating a high gradient, high flow regime, the other a low-gradient, sluggish flow regime.

Seal longevity depends in part upon the amount of groundwater coming into intimate contact with, and dissolving, the grout per unit time. Results of the analyses indicate that, given the assumptions and simplifications inherent in the models, acceptable seal performance (i.e., acceptable increases in hydraulic conductivity of the seals) may be expected for at least thousands of years in the worst cases analyzed, and possibly much longer. One reason is that in high-flow regimes, high hydraulic heads would tend to favor relatively rapid repository resaturation after closure. This would result in a rapid return to lower-head ambient conditions, with less groundwater flowing through the seal and dissolving grout. In sluggish hydraulic regimes dissolution of grout may be accompanied by significant precipitation of such secondary minerals as gypsum, brucite, carbonates, and zeolites. These would tend to fill voids in the grout and limit increases in hydraulic conductivity over much longer periods.

## INTRODUCTION

This paper presents the results of some first steps in assessing the usefulness of geochemical principals and computer modeling techniques for predicting long-term performance of cementitious grout as a seal material in deep geological repositories for high-level radioactive waste. Portland cement grout is a leading candidate seal material in many national repository programs. It has several desirable characteristics, including low permeability, resistance to erosion, ability to be injected into narrow fractures, ability to self-heal, long history of use and ready availability, and apparent persistence over hundreds, even thousands of years (1,2). The very long-term chemical stability of portland cement grout under repository conditions has been questioned, however.

The primary objective of this investigation is to improve our understanding of the chemical nature of alteration of cementitious grout seal material, and to develop a theoretical basis for estimating grout performance over very long time periods. The work described herein has been performed as part of Phase III of the Stripa Project, an international cooperative effort in the study of nuclear waste management initiated in 1980. Hydrogeological and geochemical investigations of the Stripa Granite rock mass were undertaken in Phases I and II. Phase III, which began in late 1986 and is scheduled for completion in 1991, has several investigative objectives, including the identification, selection, and evaluation of materials for the long-term sealing of fractured rock. A portion of this work was performed under contract with RE/SPEC Inc.

## APPROACH TO THE INVESTIGATION

Cement is an engineered material that is composed primarily of calcium-aluminum-silicate-hydrates that exhibit varying degrees of crystallinity. Most of these phases are metastable, which raises concerns regarding the grout's

long-term persistence. Knowledge of the kinetics of grout phase alteration, the mechanisms, products, and rates of reactions, is essential to calculate the longevity of grout, but that knowledge is largely lacking at present.

The authors decided to take a thermodynamic approach, using a simplified grout model, available thermodynamic data, state-of-the-art geochemical computer models, natural groundwaters, and a set of bounding hydrologic conditions. These are used to estimate the amount of grout that would be dissolved upon equilibration with groundwater, the alteration products formed, and the effect of the dissolution on the performance of the grout as a hydrologic barrier.

## GROUT MODELS

The grout model used in our work to date is based on a simplified Type V portland cement. The bulk composition was modified to include six components: CaO, SO<sub>3</sub>, Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, O<sub>2</sub>, and H<sub>2</sub>O. A normative calculation was performed to obtain an assemblage of cement phases to be used in the modeling, namely tobermorite, hydrogarnet, and ettringite. Tobermorite (Ca<sub>5</sub>Si<sub>6</sub>O<sub>17</sub>·10.5H<sub>2</sub>O, 14-angstrom) is thought to be an important constituent in CSH gel of hydrated portland cement (3,4). X-ray diffraction patterns of CSH gel often show weak reflections, indicating the presence of tobermorite or a similar phase in crypto-crystalline form. In addition, tobermorite crystals in close association with the CSH gel have been observed in SEM photomicrographs (4). Sarkar, et al. (5), in a derivation based on thermodynamic considerations, suggest that excess silica added to cement, as in pozzolanic portland cement, reacts with Ca(OH)<sub>2</sub> to form additional tobermorite during hydration. Ettringite (Ca<sub>6</sub>Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>(OH)<sub>12</sub>·26H<sub>2</sub>O) is commonly formed during hydration of gypsum-bearing cements, and hydrogarnet (Ca<sub>3</sub>Al<sub>2</sub>O<sub>6</sub>·6H<sub>2</sub>O) seems to be a reasonable proxy for the products of hydration of C<sub>3</sub>A (4).

In the norm calculation sulfate content in the cement was assumed to control ettringite formation. CaO and Al<sub>2</sub>O<sub>3</sub> were combined with sulfate until it was exhausted. Hydrogarnet was calculated next by combining CaO and Al<sub>2</sub>O<sub>3</sub> until all of the Al<sub>2</sub>O<sub>3</sub> was used. The remaining CaO was combined with SiO<sub>2</sub> to form tobermorite. SiO<sub>2</sub> was assumed to be in excess as pozzolan. The calculated molar proportions of the phases in the model grout are 33 tobermorite, 2 hydrogarnet, and 1 ettringite.

#### MODELING OF THERMODYNAMIC EQUILIBRIA

Thermodynamic data on the phases present in the model grout were culled from several sources (5,6,7,8,9). At this stage in the investigation it is necessary to assume crystallinity and stoichiometry for the grout phases, since data are not available for amorphous or semicrystalline phases. [A sensitivity analysis is presently underway to assess the effects on the final results of raising (making less negative) the Gibbs free energy of formation of the crystalline grout phases in order to simulate the higher free energies one might expect in semiamorphous phases.] It has been suggested that the value for 14Å tobermorite may not be very different from that of actual CSH (10), so that has been used in this analysis.

The computer code PHREEQE (11,12) was used first to test the feasibility of using a computer model with a highly simplified grout model. PHREEQE is a solubility/speciation/ reaction path program developed by the U.S. Geological Survey which can be run on a personal computer and has several capabilities: the concentrations of species in a solution, e.g., natural groundwater, can be determined; the activities and activity coefficients of the dissolved species can be calculated; the state of saturation of the solution with respect to a range of solid phases can be calculated; and the successive compositions of a solution, as a solid phase reacts with the solution, can be predicted. Since PHREEQE can accommodate only a single solid phase, the grout model was simplified to tobermorite, which comprises over 90% of the three-phase model grout.

Progressively more detailed grout models are being analyzed with the geochemical codes EQ3NR/EQ6 (EQ3/6) (6,13). These, too, are solubility/speciation/reaction path codes, but they exhibit several improvements over other codes: (1) several solid phases may be incorporated into the model; (2) the codes' database is extensive and well-documented; (3) waters with high ionic strength may be considered; (4) temperature may be varied throughout a run to simulate thermal history in a repository environment; (5) kinetic data may be incorporated to calculate reaction rates; (6) mineral solid solutions may be considered; and (7) mass balance constraints are applied to H<sub>2</sub>O. This last point is particularly important when dealing with the dissolution and precipitation of hydrated phases. The interaction of

groundwater with the model three-phase grout was analyzed with EQ3/6.

#### HYDROLOGIC MODELS AND GROUNDWATER CHEMISTRY

In this investigation, two bounding scenarios were analyzed to assess the potential for groundwater to dissolve the model grout:

- A chemically "open" system, in which groundwater permeates the grout seal, dissolves some of the grout, and transports the dissolved grout material away and out of the seal. As the altered groundwater exits the seal, unaltered groundwater enters the seal and the process is repeated. As the groundwater flows through and reacts with the grout in this manner, porosity and hydraulic conductivity increase.
- A chemically "closed" system, in which groundwater permeates the seal and remains in intimate contact with the grout, precipitating secondary phases due to compositional changes in the groundwater. Increased permeability that might arise due to grout dissolution is partially offset by the precipitation and infilling of pore spaces by secondary phases.

In both scenarios Darcy flow is assumed, as is thermodynamic equilibrium between groundwater and grout. The open system scenario is reasonable as a bounding case in a hydrogeologic regime where there are relatively high hydraulic gradients, and groundwater could be expected to enter and saturate the seal and then flow out, driven by the gradient at the seal. The closed system scenario is reasonable for a very sluggish hydrogeologic regime where groundwater saturates the seal material and remains within the seal for a significant period of time. Taken together, the open and closed systems analysis brackets expected performance of the grout.

The compositions of groundwaters from crystalline rocks of the Canadian Shield (14) were used to react with the model grout (Table I). These are predominantly calcium-sodium-chlorine groundwaters; those used in the analyses range from fresh (Total Dissolved Solids, TDS, 1000 mg/l) to saline (10,000 mg/l TDS 100,000 mg/l).

#### POROSITY/HYDRAULIC CONDUCTIVITY CHANGES IN GROUT

An expression which calculates changes in hydraulic conductivity resulting from changes in porosity was developed by correlating two types of data from concrete experiments (15,16,17,18). One set of data relates the water/cement ratio of the initial mix to the measured porosity of the cement paste. The second data set relates water/cement ratio to the measured permeability (or hydraulic conductivity) of the paste. By correlating the two sets of data by their common factor, water/cement ratio, a

TABLE I  
Geochemistry of Representative Groundwaters in the Canadian Shield<sup>1</sup>

	FRESH <sup>2</sup>		BRACKISH <sup>2</sup>		SALINE <sup>2</sup>		
	YK-62	YK-65	YK-73	T-83	T-86	T-87	S-154
Depth (m)	130	175	457	305	610	671	1006
pH	7.40	7.25	6.65	6.30	6.54	6.40	8.20
Temp (°C)	8.0	--	12.5	9.5	13.5	13.5	19.5
Density	1.000	1.000	1.006	1.000	1.013	1.015	1.014
Ca, mg/l	80	103	1400	820	4540	4840	4470
Na, mg/l	107	26	1600	908	2740	2930	2300
Mg, mg/l	42.0	46.0	174	145	160	233	2.0
K, mg/l	4.3	5.7	29.8	7.8	32.1	92.6	23.1
Sr, mg/l	---	---	--	14.6	79.7	98.3	72.0
Cl, mg/l	51	4	5250	3120	12600	13700	11300
Br, mg/l	0.40	0.18	96.8	34.4	111	115	78.7
SO <sub>4</sub> , mg/l	227	197		28.0	1.0	444	533
HCO <sub>3</sub> , mg/l	341.0	350.0	280.0	263.0	55.0	28.0	15.0
SiO <sub>2</sub> , mg/l	---3	---3	---3	6.4	8.50	5.30	5.80

<sup>1</sup> From Frappe, et al (1984)

<sup>2</sup> Classification according to Total Dissolved Solids (TDS); Brines > 100,000 mg/l; Saline 10,000-100,000 mg/l; Brackish 1000-10,000 mg/l; and Fresh < 1000 mg/l

<sup>3</sup> Values for SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> used but not presented here are from Gray (Personal Communication, 1988) or deduced by using EQ6 to equilibrate groundwaters with quartz (to obtain SiO<sub>2</sub> values) and montmorillonite (to obtain Al<sub>2</sub>O<sub>3</sub> values).

relationship between porosity and hydraulic conductivity was derived:

$$\Delta K = K_0 * 10^{(11.14 * \Delta n)} - K_0 \quad (\text{Eq. 1})$$

where

$\Delta K$  = Change in hydraulic conductivity of the concrete

$K_0$  = Initial hydraulic conductivity of the concrete

$\Delta n$  = change in porosity of the concrete.

Since the data used to develop this relationship were taken from experiments performed over many years in different laboratories, and various cement types (chemistries) were analyzed, there is some variability. However, plots of porosity vs. water/cement ratio and hydraulic conductivity vs. water/cement ratio show that the slopes of the trends for each data group are strikingly consistent. Therefore, the relationship derived relates changes in porosity to changes in hydraulic conductivity.

Changes (increases) in hydraulic conductivity were calculated for the partially dissolving grout, using an initial porosity of 30 percent and initial hydraulic conductivity of 10<sup>-12</sup> meters/second. The initial conductivity value was established in a related study (19) through direct measurement. This approach is considered conservative for several reasons. First, all porosity in the grout is assumed to be interconnected. Second, the tendency of the reference

grouts to "heal" themselves during laboratory measurements of hydraulic conductivity over time (i.e., the hydraulic conductivity has been observed to decrease over successive measurements) has been ignored. Third, in these analyses, a hydraulic conductivity of 10<sup>-12</sup> meters/second or more is assumed for the unaltered grout; in practice, lower conductivities (i.e., 10<sup>-13</sup> meters/second or less) are achievable (19).

## RESULTS

### Analysis of Simple Grout Model Using PHREEQE

Seven different groundwater compositions: two fresh (YK-65 and YK-62), two brackish (T-83 and YK-73), and three saline (S-154, T-86, and T-87) were used in the modeling to represent a wide range of groundwater chemistry (14). Concentrated brine compositions were not used because PHREEQE is limited to solutions with lower ionic strengths. The grout was assumed to be entirely tobermorite. This limitation was driven by the code, i.e., PHREEQE is able to calculate the equilibration of an aqueous solution with a single solid phase. Having selected the phase upon which to base the dissolution model, the two different scenarios described above depicting the dynamics of groundwater interaction with a grout-sealed fracture (closed system/slow flow and open system/fast flow) were evaluated. The approach taken is highly conservative because, in the absence of kinetic data, all groundwater is assumed to become completely saturated with tobermorite, and all porosity is assumed to be interconnected. A

nonconservative but reasonable assumption was also made, and that is that the porosity is uniformly distributed throughout the grout.

The "closed system" analysis was performed in the following manner. Each groundwater was equilibrated with the tobermorite grout. The number of moles of tobermorite dissolved in one kilogram of groundwater was calculated, and the resulting altered groundwater composition was determined, including changes in pH and ionic strength. Possible and reasonable secondary mineral assemblages resulting from the reaction of the groundwater with tobermorite were allowed to precipitate.

Net changes in volume and porosity calculated from dissolution of the tobermorite and precipitation of stable minerals were determined, as well as groundwater compositional changes resulting from the dissolution and precipitation. The changes in hydraulic conductivity with porosity were calculated, using the relationship described above [Eq.(1)] and assuming a value for initial hydraulic conductivity of the grout of  $1 \times 10^{-12}$  meters/second. In addition, the initial porosity was assumed to be 30 percent, which is typical for pastes with water/cement ratios of interest, i.e., approximately 0.4 (15,16,17,18).

The PHREEQE results indicate that the groundwaters are highly undersaturated with respect to tobermorite, suggesting that on a thermodynamic basis it will dissolve. In addition, the groundwaters appear to be saturated with respect to carbonates (e.g., calcite, dolomite), quartz, and plagioclase (e.g., anorthite), suggesting that the groundwaters are in thermodynamic equilibrium with granitic rocks and common secondary minerals.

Dissolution of tobermorite and formation of a stable assemblage dominated by silica minerals and carbonates results in primarily positive volume changes and decreased hydraulic conductivity. (The positive volume changes may be an artifact of PHREEQE's inability to calculate changing water balance as hydrated phases react.) Of these, the assemblages containing amorphous silica result in slightly less positive or slightly negative volume changes. Positive volume changes, as one might expect, result in lower hydraulic conductivities, whereas negative volume changes result in higher hydraulic conductivities. The greatest increases in hydraulic conductivity predicted by the model were on the order of 0.5 percent.

In the "open system" analysis, the volume changes produced from the reaction of one liter of each groundwater with tobermorite were calculated, but without the accompanying precipitation of secondary phases. The groundwater thus modified was assumed to flow out of the seal carrying with it the dissolved grout constituents. The resulting decrease in volume of the grout mass due to dissolution is assumed to occur uniformly throughout the

grout, resulting in a general increase in the uniformly distributed and interconnected porosity.

Further, the dissolution of tobermorite over time was related to changing (increasing) hydraulic conductivity to obtain an estimate of how long the cementitious grout would maintain some level of performance under a conservative but realistic set of hydrologic conditions. To accomplish this, a hydraulic gradient was assumed, and groundwater was allowed to enter the seal one liter at a time, dissolve grout, and exit the seal. With each liter of groundwater, porosity and hydraulic conductivity increased slightly. As a result each subsequent liter entered the seal a little more quickly.

The logic is as follows: in order for water to transport material out of the seal, it first has to get in. The amount of grout removed with time -- hence increase in grout porosity/permeability with time -- is a direct function of the rate at which water comes into contact with and dissolves the grout. Therefore, the limit on a seal's decrease in performance is determined by: 1) the amount of water traveling through the seal per unit time, which is a function of hydraulic head and hydraulic conductivity, and 2) the solubility of the grout phases.

The hydraulic gradient was calculated from the length of the grout seal, which was conservatively assumed to be 0.5 meter (the minimum seal length expected to be encountered), and a time sequence of changing hydraulic heads. The head was assumed to be 1,000 meters initially. This derives from the assumed depth of the repository, and stems from the assumption that the host rock outside the repository is saturated while that inside the repository is unsaturated for the first 1,000 years after closure. After 1,000 years, it is assumed that the repository horizon becomes resaturated with groundwater and the ambient gradient is restored. For the period beyond the first 1000 years until seal failure, the head was conservatively assumed to be one meter.

Figure 1 presents the results of the calculations of change in hydraulic conductivity with time. Tobermorite grout appears to be relatively long-lived in saline water T-86, as after two million years there is insignificant change in the hydraulic conductivity of the grout. The seal performs effectively for approximately 1.4 million years in brackish water YK-73 and fresh water YK-65. In the worst case, brackish water T-83, the seal performs for about 600,000 years. From this analysis, the considerably lower increases in hydraulic conductivity due to tobermorite dissolution in saline water T-86 suggest that saline groundwaters are less reactive with simplified cementitious grout than fresh and brackish waters. This may be due in part to the fact that, in general, water containing a higher TDS has less capacity to dissolve material than lower TDS water. Because of the

\* PHREEQE is not able to assess solid solution; thus, calcite-dolomite and anorthite reflect the Ca-Mg components of calcite and the Ca component of plagioclase, respectively.

\*\* PHREEQE and EQ3/6 perform their calculations with water units of one kilogram, which has an approximate volume of one liter. For convenience "liter" is used in this discussion.

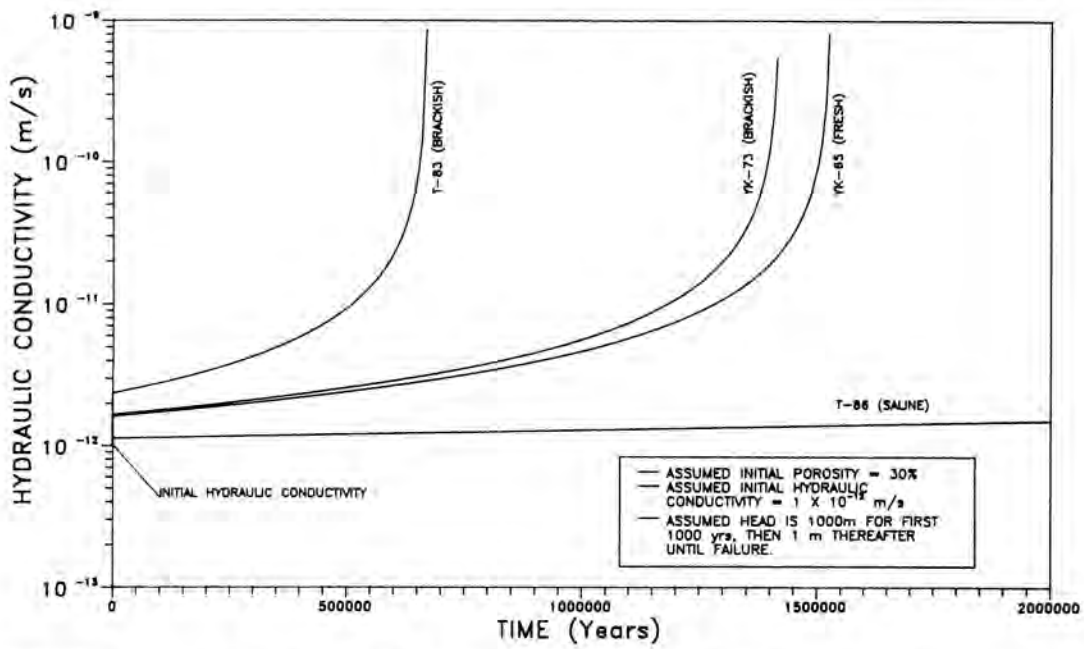


Fig. 1. Results of PHREEQE Modeling--Changes in Hydraulic Conductivity With Time of One-Phase "Grout" From Interaction with Four Canadian Shield Groundwaters, No Secondary Minerals Precipitated.

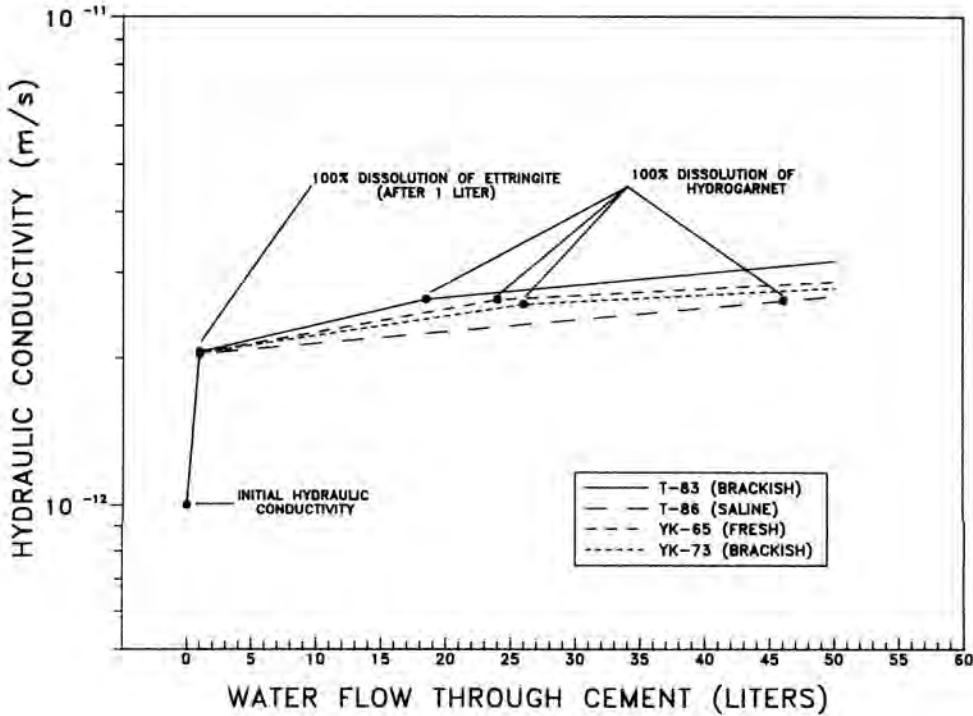


Fig. 2. Results of EQ3NR/EQ6 Modeling--Changes in Hydraulic Conductivity of Three-Phase "Grout" Due to Liter-By-Liter Interaction of Four Canadian Shield Groundwaters, No Secondary Minerals Precipitated.

tobermorite's composition, Ca and Si concentrations may be particularly important.

#### Analysis of More Complex Grout Model Using EQ3NR/EQ6

The model grout composed of 33 tobermorite + 2 hydrogarnet + 1 ettringite was equilibrated with four Canadian Shield groundwaters, using EQ3/6, for the closed system/slow flow and open system/fast flow scenarios. As with the PHREEQE analyses, for the closed system one liter of groundwater was assumed to permeate the seal, dissolve a portion of the grout, and precipitate secondary phases. The dissolution and precipitation resulted in a two-fold increase in hydraulic conductivity with all four groundwaters, corresponding to an increase from  $1 \times 10^{-12}$  meters/second to  $2 \times 10^{-12}$  meters/second. As a result of the grout-groundwater interactions, ettringite dissolved completely; hydrogarnet and tobermorite dissolved to a much lesser degree. The secondary mineral assemblage that resulted includes carbonates, gypsum, brucite, zeolites, and calcium-silicate-hydrates.

In the open system analyses, as before, each liter of groundwater was assumed to permeate the grout and exit the seal with its dissolved constituents. Figure 2 presents liter-by-liter changes in hydraulic conductivity of the grout for each groundwater, with the points indicated where ettringite and hydrogarnet are completely dissolved. Note that ettringite is exhausted in the first liter of all four groundwaters, resulting in an approximate two-fold increase in hydraulic conductivity. Thereafter liter-by-liter hydraulic conductivity increases are much smaller. After disappearance of the last hydrogarnet (with the 46th liter in the case of saline T-86) the grout solubility and performance is controlled by tobermorite, as in the single-phase grout model.

In comparing the open system analyses for the one-phase and three-phase grouts, it becomes clear that the most significant consequence of increasing the complexity of the grout is the relatively large increase in hydraulic conductivity during the initial period of high hydraulic head. As stated above, the limit on a seal's decrease in performance is determined by: (1) the amount of water traveling through the seal per unit time, which is itself a function of hydraulic head and hydraulic conductivity, and (2) the solubility of the grout phases. The more soluble hydrogarnet and particularly ettringite dissolve early on, thereby allowing groundwater to flow through the seal at a greater rate, resulting in more grout dissolved per unit time.

This is borne out by comparing Figs. 1 and 3. While they appear similar, the assumptions regarding duration of high hydraulic head are different. In Fig. 1, from the PHREEQE-modeled one-phase grout analysis, an initial head of 1000 meters for 1000 years is assumed, with an ambient head of 1 meter thereafter. In Fig. 3, which presents results of the EQ3/6-modeled three-phase grout analysis, the initial head is 1000 meters for the first 100 years, with a head of 1 meter thereafter.

It was found that the magnitude and duration of the relatively high hydraulic heads expected to prevail prior to

repository resaturation can have a dramatic effect on grout seal durability. If high heads persist, more water will percolate through the seal and dissolve grout, thereby shortening the seal's life. However, high heads prevailing prior to closure of the repository would probably favor relatively rapid resaturation and a quick return to ambient conditions. Following this logic, low heads would result in less groundwater flowing through a seal, thereby prolonging its life; on the other hand, resaturation and return to ambient conditions would occur more slowly.

The significance of the magnitude and duration of the initial hydraulic head can be grasped by comparing Figs. 3 (initial head 1000 meters for 100 years) and 4 (initial head 500 meters for 500 years). If it is true that high hydraulic heads will tend to shorten the time for repository resaturation, then a site that favors long-lived cement grout performance may be one where a high water pressure exists, but is accompanied by a low ambient hydraulic gradient. An actual resaturation time could be calculated from a realistic estimate of the volume of void space in a repository readied for closure. It may happen that the 100- to 500-year resaturation times discussed here are overly conservative.

#### PLANS FOR FURTHER WORK

The results of what we have done so far are promising. It is clear also that more effort is needed to improve several of the assumptions which are critical to this kind of predictive analysis. It is anticipated that subsequent investigations will involve grout models of increasing complexity, evaluation of assumptions inherent in the thermodynamic modeling, and more realistic simulation of conditions (e.g., higher temperatures) expected in high-level waste repositories. Following are brief descriptions of several possible lines of inquiry.

- The search for kinetic information on the dissolution and precipitation of grout phases and analogs will continue.
- Iron will be added to the cement system. This will add an important component to the grout model, as well as allow additional secondary phases such as clays in the closed system/low flow analyses.
- A sensitivity analysis will be performed to ascertain the effects of uncertainty in the thermodynamic data on the modeling results. The effect of using tobermorite as a proxy for CSH in cement, for example, will be examined by varying the Gibbs free energy of formation of tobermorite to make it "more amorphous" or "less crystalline." This is expected to add considerable confidence to subsequent efforts.
- With EQ3NR/EQ6 temperature can be ramped up or down to simulate specific *thermal histories*. The grout-groundwater interactions modeled to date will be modeled at higher temperatures to simulate near-field repository conditions.

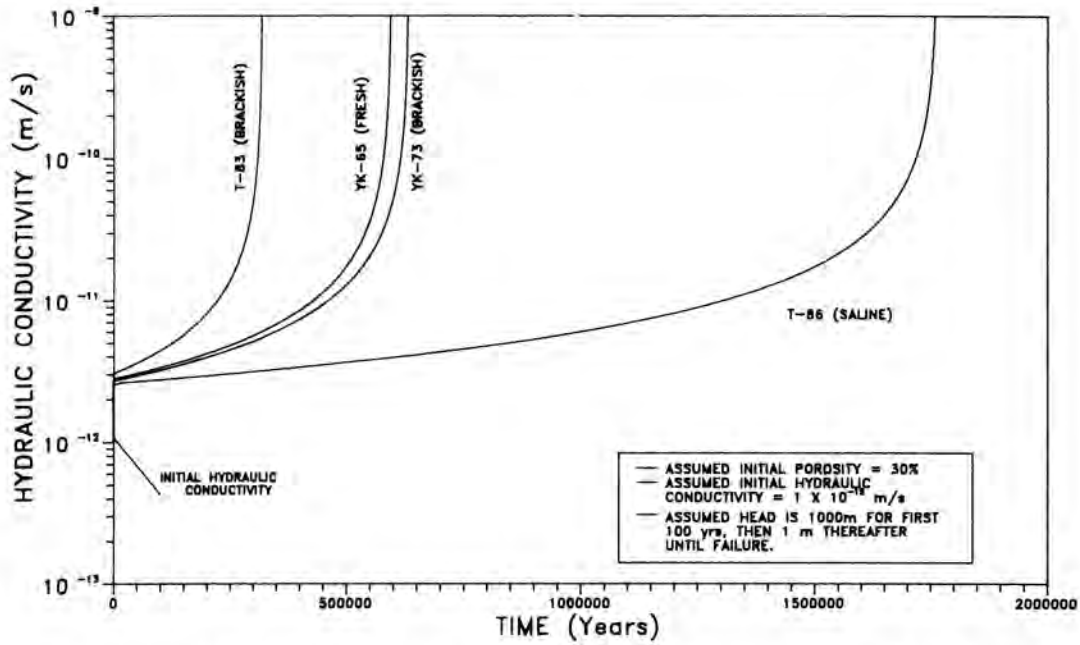


Fig. 3. Results of EQ3NR/EQ6 Modeling-Changes in Hydraulic Conductivity With Time of Three Phase "Grout" From Interaction With Four Canadian Shield Groundwaters, No Secondary Minerals Precipitated, High Initial Hydraulic Head of Short Duration (Compare with Fig. 4).

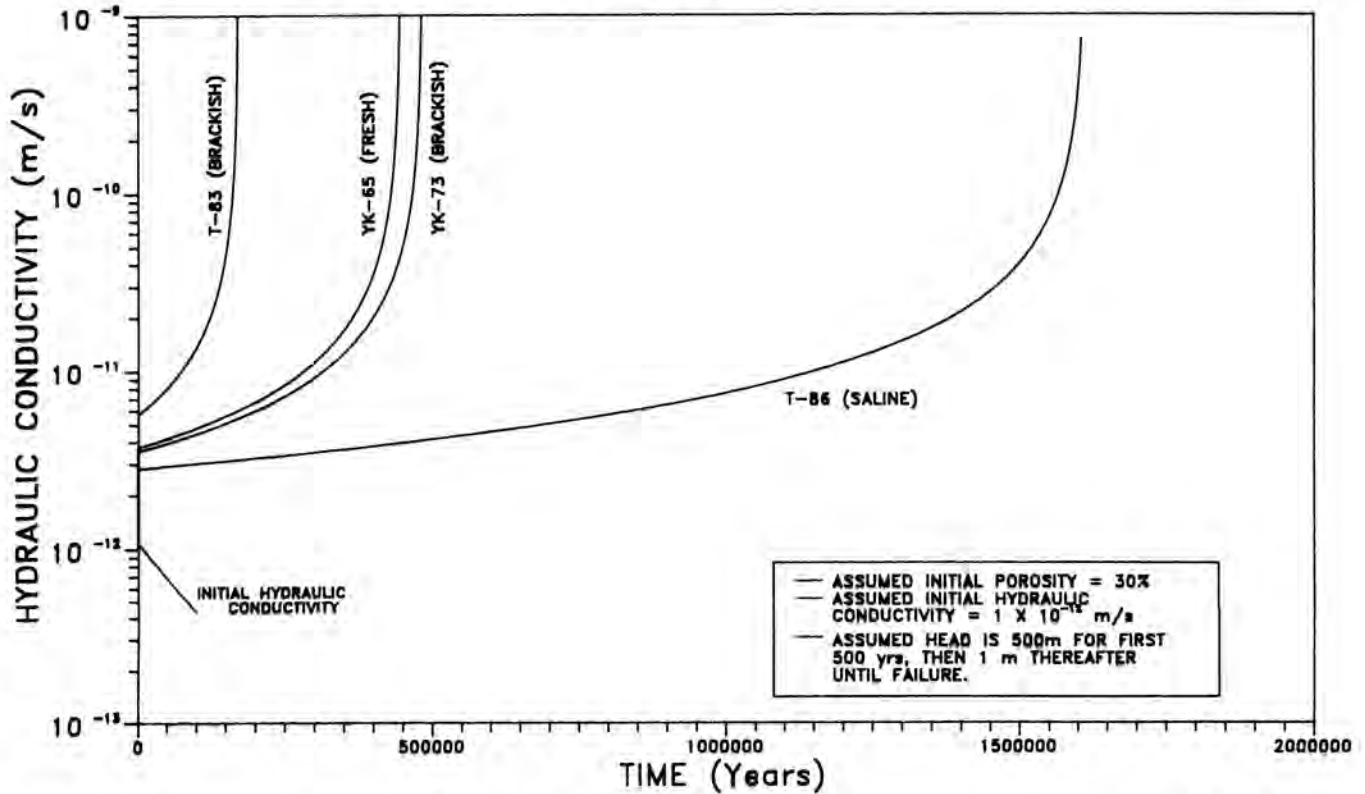


Fig. 4. Results of EQ3NR/EQ6 Modeling-Changes in Hydraulic Conductivity With Time of Three-Phase "Grout" From Interaction With Four Canadian Shield Groundwaters, No Secondary Minerals Precipitated, Moderate Initial Hydraulic Head of Moderate Duration (Compare with Fig. 3).

- Other components will be added to the grout-groundwater system, such as host rock minerals, radionuclides, and man-made materials.
- The relationship between changes in porosity and hydraulic conductivity in grout will be refined as more data become available.

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