Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

EARTH SCIENCES DIVISION

Presented at the Two-Phase Flow in Fractured Rock, Berkeley, CA, November 3–5, 1993, and to be published in the Proceedings

Two-Phase Flow in Fractured Rock

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November 1993

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Proceedings:

Two-Phase Flow in Fractured Rock

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University of California
Berkeley, CA 94720
November 3-5, 1993

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MASTER

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Report from
Workshop on Two-Phase Flow in Fractured Rock

Sponsored by
International Programs Coordinating Group/US DOE
SKB and Nagra
November 3-5 1993, Berkeley California

Introduction

This report gives the results of a three-day workshop on two-phase flow in fractured rock. The workshop focused on two-phase flow processes that are important in geologic disposal of nuclear waste as experienced in a variety of repository settings.

The workshop was sponsored by the Yucca Mountain Project (YMP) /International Programs Coordinating Group (IPCG) in cooperation with the Swedish Nuclear Fuel and Waste Management Co. (SKB) and the Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra). Part of the charter of IPCG is to facilitate information exchange between international programs and the YMP. To that end, IPCG decided in the Spring of 1993 to sponsor a series of international workshops. Subsequently, SKB expressed interest in holding a workshop on two-phase flow in fractured rock, and this topic was chosen for the first IPCG workshop. Both Nagra and WIPP were invited to join in the workshop as these participants face problems with two-phase flow in fractured rock and have considerable experience to bring to the table. Both Nagra and SKB's interest stems from low, intermediate and high-level waste problems. The workshop was hosted by Lawrence Berkeley Laboratory (LBL). The conference organizers were Jane Long (LBL), Peter Davies (Sandia), Olle Olsson (SKB), and Piet Zuidema (Nagra).

Goals and objectives of the workshop

The goals and objectives of the workshop were threefold:

• Exchange information
• Describe the current state of understanding
• Identify research needs

Process and Structure

Participants were invited to the workshop based on their direct research experience in two-phase flow in fractured media. Participants were asked to prepare abstracts containing a description of key issues and submit these in advance of the workshop; these were distributed the week before the workshop started.

The first day of the workshop was designed as an information exchange. Three types of talks were given. The first set gave an overview of the key issues related to two-phase flow in fractured rock from the perspective of each of the four repository programs represented at the workshop:

- Nagra (Piet Zuidema)
- SKB (Olle Olsson)
- WIPP (Peter Davies)
- YMP (Bo Bodvarsson)

Following these, three speakers were asked to address the state-of-the-art:

- Modeling perspective -- Karsten Pruess
- Laboratory perspective -- Bob Glass
- Field Experiments perspective --Ed Kwicklis

Finally, each of the remaining participants were asked to give a ten minute talk providing information on what two-phase processes they were working on, what their approach was, what has been learned, and what issues remain unsolved. Each was asked to comment on how their work related to the following programmatic issues:

1. How will waste-generated gas affect repository integrity?
2. How might volatile organic carbons (VOC's) be transported in the gas phase?
3. What "artifacts" or complexities do two-phase flow conditions cause in characterization tests designed to determine undisturbed properties of the rock?
4. What are the liquid and gas fast flow paths under unsaturated conditions?
5. How will heat affect transport and repository integrity?
6. How does trapped gas affect the performance of the repository?
7. How will the introduction of man-made materials affect two-phase flow in fractures?

On the second day, the participants were divided into four subgroups. Each group was asked to address a series of two-phase flow processes. The following groups were defined to address these processes:

Group 1: Basic Flow Processes	Group 3 Complex Flow Processes
Lead: Karsten Pruess	*Lead: Bob Glass*
Members: Piet Zuidema, Georgia Destouni, Ed Kwicklis, Rick Beauheim, Kunio Watanabe, Gerhard Mayer, Jiamin Wan	*Members: Jil Geller, Peter Persoff, Olle Olsson, Stefan Finsterle, Rainer Senger*
- Wetting/draining and sequential wetting/draining - Threshold pressure effects in low permeability media - Geometric control - Transport (including colloids) - Processes/conditions leading to strongly preferential flows - Single vs. multicomponent two-phase flow	- Fingering instabilities - Excavation effects - Drying /evaporation - Degassing/dissolution - Non-continuous flow
Group 2 Fracture/Matrix Interactions	Group 4 Coupled Processes
Lead: Bo Bodvarsson	*Lead: Peter Davies*
Members: Bob Zimmerman, Dwayne Chesnut, James Houseworth, Dwight Hoxie, Alan Flint	*Members: Christine Doughty, Cliff Ho, Tom Buscheck, Bruce Robinson*
- Matrix Imbibition/Drainage - Gas/Air Entrapment - Heat Transfer - Precipitation /Dissolution - Phase Changes - Vapor Flow Enhancement - Matrix Diffusion and Sorption	- Flow coupled to stress - Flow coupled to heat - Flow coupled to chemical processes - Coupled flow, stress, heat, and chemistry

For each process, the groups were asked to address these four issues:

1.	Describe the two-phase flow process that are important with respect to repository performance.
2.	Describe how this process relates to the specific driving programmatic issues given above for nuclear waste storage.
3.	Evaluate the state of understanding for these processes. What do we know? What don't we know?
4.	Suggest additional research to address poorly understood processes relevant to repository performance.

On the third day of the workshop, the keynote speakers and workshop organizers (Bo Bodvarsson, Peter Davies, Christine Doughty, Bob Glass, Ed Kwicklis, Jane Long, Olle Olsson, Karsten Pruess, Piet Zuidema) assembled the material generated on the second day into this report. The goal of this effort was to get the ideas quickly into written form. Emphasis was placed on getting the report out within the time frame of the workshop. Consequently the report is not a polished product. The report was circulated to participants for editing to eliminate major errors. Further, this report represents the opinions of the participants and the information available to them within the time frame of the workshop. In some cases, the expertise necessary to address certain issues was not available at the workshop. Consequently these issues were not developed in the report. Research needs which are identified have been considered relevant to at least one of the radioactive waste programs. Hence, any particular research need may not be relevant to a particular waste program.

Highlights of the Workshop

A number of themes were constantly repeated by the participants. These themes stand out as important highlights that should have a strong impact on repository programs. These are as follows:

1. We do have a relatively complete understanding of a broad range of the physical processes affecting two-phase flow behavior under controlled conditions for simple geometric conditions. During the workshop the key processes for the performance of the repositories discussed were identified and listed (see report from working groups below). The list of processes is considered to be relatively comprehensive and no major processes are expected to be missing.

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2.   Our abilities to address two-phase flow processes experimentally in the laboratory at a small scale is good. However, there is a lack of data on fracture aperture distributions for real fractures which makes it difficult to assess whether laboratory experiments and corresponding model simulations provide realistic representations of reality. Fracture aperture data is essential in order to relate two-phase flow properties to single fracture characteristics.

3.   Field testing, however, is much more difficult and confounded by imprecise boundary conditions, initial conditions and the instigation of two phase flow processes that are not of primary concern for experiments that are designed primarily for model validation or characterization purposes. Appropriate designs for well constrained, two-phase *in situ* experiments are not generally well known. However, *in situ* heater tests can be designed to test fundamental hypothesis about field-scale behavior in response to heat generating waste.

4.   The processes and geometric features which dominate two-phase flow behavior at larger scales and in the complex geometry commonly found in fractured systems are not understood. The scientific foundation for scaling up laboratory data or small scale, *in situ* behavior to scales representative for repository behavior is very weak. There is even great uncertainty of which processes observed in the small scale become dominant at larger scales for a given set of boundary conditions. This is essentially due to a lack of quantitative knowledge of how these processes are affected by more complex geometric settings.

5.   Representative characterizations of two-phase flow phenomena in fractured rocks are not available, and this results in great uncertainty in predicting two-phase flow behavior, in many cases even qualitatively. There is a general lack of data on characteristic curves (relative permeabilities as a function of saturation) for fractured media. There is also uncertainty as to how such data should be collected, and the representativeness of laboratory data to initial conditions. We do not yet know how to build the small scale processes into models to predict larger scale response or "effective" continuum models and their "effective" properties. It is presumed (or hoped) that knowledge of small scale processes will somehow yield understanding of large scale system behavior.

6.   Our modeling capabilities are excellent, but stunted by the lack of systematic model testing through design and implementation of laboratory and field experiments. Every laboratory experiment and field test must be designed, predicted, and interpreted by models.

Reports from the Working Groups

The reports form each of the four working groups are given here. Each working group was asked to follow the outline given at the top of page 4. Each group did this in a different way. Group 1, for example, discussed all the processes, then all the relationships to programmatic issues, then what is known about all the processes and what should be done about all of them. Consequently, the products of Group 1 can be thought of as a type of introduction. The other three groups went through the outline process by process. Group 4 added another layer of organization by grouping processes. Consequently, more detailed analysises are found in the reports of Groups 2, 3 and 4.

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Report from Group 1: Basic Flow Processes

Before listing the relevant processes it was decided to set the scene by defining the features to be (potentially) considered in the system of interest. The following features (players) are considered to be important:

- solid ([fractured] porous media)
- water (in liquid and gas phase)
- gas (free gas phase and dissolved in water)
- solutes
- colloidal particles (including microorganisms)

Each of the "players" has distinct constitutive properties. The behavior of the system will be governed by the external forces acting on the system and the interactions (also including forces) between the different "players". For the interactions currently considered to be important, both equilibrium and non-equilibrium situations may occur. By having set the scene with this general description, processes, events and phenomena were listed according to the sequence in which they may occur in the different two-phase systems of interest (release of repository generated gas for repositories with initially fully saturated host rock, flow under unsaturated conditions, ventilated underground openings below the water table).

Basic Flow Processes

Processes, events and phenomena that may occur for repositories below the water table:

- gas generation
- dissolution of gas in water
- formation of a free gas phase
- compression of gas phase
- entry of gas phase into voids and displacement of the water (which may contain dissolved gas) by the gas phase: the interaction between gas, solution and solid will lead to capillary forces (including threshold pressure effects)
- deformation of the solid (e.g., fracture dilation)
- migration of water, gas and gas-water mixtures (which in itself involves a large variety of phenomena such as channeling and fingering)
- exsolution of gas due to pressure decrease ("generation" of gas)
- processes leading to changes in properties of the "players" (e.g. microbially mediated chemical interactions between solution and solid leading to different transport properties of the solid material)

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- events leading to changes in the properties of the solid such as changes in the properties of fractures or generation of new fractures (e.g., due to seismic events, rock mass instabilities, thermo-mechanically induced events)
- transport of colloidal, dissolved and gaseous species in the gas or water phase or at the interface between gas and water (which in itself involves a large variety of phenomena)

   Processes, events and phenomena that may occur at an unsaturated site:

- infiltration (diffuse, focused)
- ponding, release from ponds
- evapotranspiration
- vapor diffusion (natural geothermal gradients, thermal loading)
- migration of water, gas and gas-water mixtures (which in itself involves a large variety of phenomena such as channeling and fingering) and may be affected by gravity, thermal gradients, interfacial forces, osmotic forces, viscous forces, inertial forces etc.
- capillary barriers
- boundary effects (e.g., outflow into repository openings)
- events leading to changes in solid properties such as changes in the properties of fractures or generation of new fractures (e.g., seismic events, rock mass instabilities, thermo-mechanically induced events)
- processes leading to changes in properties of the "players" (e.g., microbially mediated chemical interactions between solution and solid leading to different transport properties of the solid material)
- drying (e.g., due to ventilation) and wetting

For a (ventilated) underground opening below the water table, processes, events and phenomena similar to those listed above may occur.

Relation of Processes to Programmatic Issues

   For those repositories which will be located below the water table, gas migration distance (also the spatial continuity of the free gas phase) and gas pressure buildup are critical questions. For repositories that may be located in the unsaturated zone where a free gas phase already exists, the relevant performance issues are quite different. The critical issues for Yucca Mountain seem to be availability of water at the canister walls and - if water can get not only to but also away from the repository - both the mass flow rate of water as well as the velocity of water travel are of concern. A central issue for all repository

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settings is the question of how gas and water flows become concentrated in fractures, flow pathways, and flow mechanisms. Gas and water flows are also controlled by the stratigraphy and structural features of the site, the properties of which may be subjected to repository-induced changes (e.g., chemical effects due to leachates of man-made materials from the repository such as concrete). If matrix diffusion and imbibition of water are considered as retardation mechanisms for mobilized radionuclides, careful characterization of matrix-fracture interactions is necessary. The interactions between mobile-immobile water and gas, rock matrix, dissolved solutes and colloids needs to be understood.

A subset of the processes which are potentially of importance to Yucca Mountain are discussed below:

1. Migration of water, gas and gas-water mixtures (including phenomena such as channeling and fingering) - The dependence of magnitude of flow rates, flow mechanisms (fracture versus matrix flow, diffuse or concentrated flow), and flow directions on moisture state and the inability to change and control moisture state for large volumes of rock, impact our ability to make observations at a large scale (PI#3). The possible dependence of flow paths on flow rates complicate predictions of flow paths under flow rates different from those at present (PI#4). Channeling will reduce the wetted surface area of the adjacent rock, limiting the importance of matrix diffusion/imbibition as a retardation mechanism for radionuclide transport (PI#4).

2. Vapor diffusion (thermal loading) - Water vapor generated by waste heat may be channeled toward and condense at just a few locations above the repository, resulting in extremely uneven saturation distributions. YMP modeling studies have shown that vapor flow channeling (or focusing) can occur under a wide range of thermal loading conditions, including those that generate sub-boiling as well as boiling conditions (Buscheck and Nitao, 1993a). Because water vapor flow may be highly channelized (process 1), the locations of largest saturation may be difficult to predict (PI#4, PI#5).

3. Boundary effects (e.g. outflow into repository openings) - Characterization of the degree to which flow is being channelized in the mechanically undisturbed rock may be difficult to infer because of aperture changes associated with drift excavation. Capillary barrier effects created by unsaturated conditions tend to cause water to flow around rather than into an open drift, biasing observations (PI#3). Boundary effects may also lead to enhanced channeling of the inflow into underground openings (PI#4)

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4.   Processes (e.g.. geochemical alteration of host rock due to interaction with leachates of man-made materials from the repository) and events (e.g.. seismic events. rock mass instabilities. thermo-mechanically induced events) leading to changes in solid properties such as changes in the properties of fractures or generation of fractures - Conduits introduced (or enlarged) as a result of any of these processes have the potential to intercept perched water bodies that may be created at some future time either by natural infiltration or as a result of heat-induced moisture redistribution. The likelihood and the impact of such a combination of events has not been investigated, but may lead to increased fast flow paths (PI#4). The clogging of porosity may lead to enhanced channeling, to perched water bodies, or hinder the interaction between fractures and matrix (PI#4).

5.   Transport of colloidal. dissolved and gaseous species in the gas or water phase or at the interface between gas and water - Many of the factors influencing the transport behavior of dissolved and colloid-transported radionulides are dependent on water saturation. These include wetted surface area of fractures, water flow paths and velocities, and matrix diffusion rates. The saturation dependence of transport behavior makes characterization more difficult than for single-phase systems.

Current State of Understanding

Many processes governing the migration of gas and liquid through fractures are understood in a theoretical sense. It is believed that given sufficient information on fracture geometry and adequate control of boundary conditions, existing models could predict the phenomena that have been observed. Difficulties arise because in field situations this information typically is incomplete. Although the geometric style of fracturing and geologic controls provide important constraints on fracture geometry and resulting flows in many field situations, sufficient geometric information will rarely be adequate to allow predictions to be made in a deterministic sense, even for steady flows. Additionally, non-equilibrium behavior that results from moving boundary conditions in transient flows, and scale-transition effects are not adequately understood. Little field data exists, although recent laboratory visualization experiments have made valuable contributions toward understanding of these phenomena. It is not known to what extent and on what scale integrational averaging would lead to simplified and predictable behavior for these cases.

Hysteretic behavior in fractures and fracture networks is not well understood. However, given that hysteresis results from geometric heterogeneity and heterogeneity exists at all scales, hysteretic behavior at scales ranging from the pore to field scales may be expected. Additional complexity may result from the fact that the mechanisms causing changes in saturation may govern this behavior.

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Transport in fracture networks is subject to the same geometric controls as is flow, and therefore to the same geometric uncertainty, even for single-phase systems. Even less is known about transport in two-phase systems. The interaction between solutes in fractures and matrix for conditions of episodic fracture flow is important for interpretation of environment tracers as well as radionuclide transport. Adequate characterization requires better understanding of fracture-matrix interactions. Effective flow and transport porosities are also critical but difficult parameters to obtain on a large-scale, although tracer tests may give local values. In order to understand the possible effects of colloids on radionuclide transport, more study is needed as to how colloids are accumulated and transported at fluid-fluid interfaces. Additional questions of colloid stability at these interfaces need to be resolved.

In single-phase fracture systems flows have often been observed to be concentrated along preferred pathways. The processes and conditions that result in preferential pathways in two-phase systems are at a very preliminary state of understanding. While the degree to which preferential flow occurs at Yucca Mountain has yet to be determined, it has been observed at Rainier Mesa in similar rock types. Based on analogies with soils and some modeling, the degree to which flow is concentrated along preferred pathways appears to be influenced not only by geometry but also by boundary conditions, which are temporally and spatially variable. Different mechanisms may cause flow concentration depending on the relative importance of gravitational instabilities, geometric variability or nonequilibrium processes.

For repository programs in which waste is to be emplaced beneath the water table, threshold pressure of fractures control the escape of waste-generated gas and associated volatile species. More field experience needs to be gained in testing fractures and in relating these pressures to flow and transport behavior for fractures with variable apertures.

Research Needs

Only a few rather limited experimental studies of two-phase (gas-water) flow in fractures have been reported in the literature. Detailed visualization and measurement of two-phase behavior has been attempted only recently, and has so far been carried out for only a few fractures or fracture replicas. The group felt that strong experimental efforts should be made to learn more about two-phase behavior in fractures. Channeling, connectivity, and flow dispersion in fractures need to be characterized and quantified. While there was a consensus that much of the flow and transport process is controlled by void space geometry, it was also pointed out that the geometric characteristics of fracture void spaces tend to be elusive in field situations, limiting the utility of geometry-based approaches to multiphase flow and transport behavior of fractures. Characteristic curves

(i.e., relative permeabilities and capillary pressures) should be measured for a broad range of different fractures, with different aperture distributions. Investigators should also address the possible difference in behavior between systems with two fluid components (water, gas) and single-component systems (water, vapor).

A very important and extremely difficult problem is to understand and quantify two-phase behavior in fractures on field scales. For the Yucca Mountain project, the single most important aspect of two-phase flow in fractures was considered to be the extent and style of preferential water flow. For repositories below the water table, such as WIPP in New Mexico and Wellenberg in Switzerland, the most important issues are gas entry (threshold) pressures, and gas fingering as affected by heterogeneity of fracture void spaces and hydrodynamic instabilities. Sampling of a large variety of fractures was deemed necessary so that results relevant to field scales could be obtained.

The difficult problem of "scale-up" is just one aspect of the larger issue of how to develop and apply methodologies that could adequately characterize the complex hydrogeology at repository sites. Experimental approaches for field observation of flow and transport on relevant spatial scales need to be developed. In addition to integration and scale-up of point measurements, other techniques need to be employed, including remote sensing, and genetic inference from tectonics and fracture coatings. The latter may shed light on how fracture channels and channelized water flow developed in the geologic past, and how they might change in the future. Opportunities for detailed characterization of formation heterogeneity will become available in underground openings, such as the ESF facility at Yucca Mountain. Among the techniques expected to be able to provide useful information on formation heterogeneity and water travel is infrared sensing for detailed mapping of evaporation. Analogs should be employed as much as possible to obtain information on space and time scales that would be relevant to repository performance. Recent laboratory evidence indicates that colloids may significantly accumulate on gas-water interfaces, which may provide novel ways for monitoring two-phase flow and transport.

It is conceivable, even likely, that continuum concepts such as relative permeabilities will only be of limited utility in describing aqueous phase flow and transport at Yucca Mountain, and gas phase flow and transport in fractures below the water table. Research is needed to determine the applicability of continuum concepts, or to develop alternative approaches, for two-phase flow and transport processes involving non-equilibrium effects, small-scale variability, and hydrodynamic instabilities.

References for the section on Basic Flow Processes

Buscheck, T.A., and J.J. Nitao, "The Impact of Repository Heat on Thermo-Hydrological Performance at Yucca Mountain," *Proceedings American Nuclear Society Topical Meeting on Site Characterization and Model Validation (Focus 93)*, Las Vegas, NV, Sept. 26-30, 1993a. Also, UCRL-JC-114791, Lawrence Livermore National Laboratory, Livermore, CA, 1993a.

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Report from Group 2: Fracture/Matrix Interaction

In this group the effects of matrix blocks on two-phase flow in fractures is considered. The group identified the following important processes:

- Matrix imbibition/drainage
- Gas/air entrapment
- Heat transfer
- Precipitation/dissolution
- Phase changes
- Vapor flow enhancement
- Matrix diffusion/sorption

Matrix Imbibition/Drainage
Description of the Processes

Matrix imbibition/drainage is (most often water and gas) exchange between matrix blocks and their surrounding fractures. It obviously affects two-phase flow in the nearby fractures as the liquid and gas are fed from the nearby matrix blocks or disappear from the fractures into the blocks. The importance of matrix imbibition/drainage is controlled by many factors including the effective surface area for flow, which is affected by fracture coating, frequency of asperities and fracture connectivity and orientations. Many of the hydrological parameters of the fractures and the matrix blocks also control the rate of imbibition/drainage including permeabilities, characteristic curves and to a lesser degree porosities.

Relation of Processes to Programmatic Issues

Matrix imbibition/drainage affects practically all of the identified programmatic issues. Because of the mass exchange (liquid and gases) between the fractures and the surrounding matrix blocks, migration issues (issues #1, 2, 4), the characterization issue (issue #3), and the man-made material issue (#7) are concerned with matrix imbibition/drainage. The issue of trapped gas (issue #6) is directly related to the invasion of a liquid front from fractures into a matrix block and similarly the invasion of gas into matrix blocks (and perhaps later dissolution). Finally, mass exchange between the fractures and matrix blocks affects heat transfer and is therefore related to the issue of thermal loading (issue #5).

Current State of Understanding

The imbibition/drainage process is conceptually well understood and can be mathematically formulated with considerable confidence. A major problem in actually

evaluating this process, however, is that detailed field data are needed. Some of these data are also very difficult to obtain, such as in-situ data on characteristics curves relating permeability, capillary pressure and saturation (Zimmerman *et al.*, 1993).

Research Needs

There are many research needs that must be carried out and completed before a full understanding of imbibition/drainage can be achieved. Some recommended research includes:

1. Field observations and predictive modeling
2. Additional laboratory experiments with real rock
3. Measurements of characteristic curves for fractures and matrix blocks
4. Model studies of scale effects and extrapolations of field and model results
5. Geothermal analog studies

Gas/Air Entrapment

Description of the Processes

As liquid water imbibes into a matrix block, due to a rise in the water table, or due to vertical infiltration through the fractures, the rate of influx may be impeded by the presence of trapped air in the matrix block. Because the travel of a liquid pulse through the fracture network is coupled to the rate at which water imbibes from the fractures into the matrix blocks, this phenomenon will affect the depth of penetration of water pulses that result from precipitation.

Relation of Processes to Programmatic Issues

For a repository located above the water table, such as the potential repository site at Yucca Mountain, an important question is whether or not water from precipitation events will reach the water table, or be imbibed by the matrix blocks before traveling down the fractures to the repository or the water table. The impact of this transient fracture-matrix interaction on the performance of a potential high level waste repository at Yucca Mountain has been investigated in a series of papers by Nitao, Buscheck, and Chesnut (see references). The answer to this question is strongly influenced by the rate at which water is imbibed into the matrix blocks. This rate may, or may not, be affected by the presence of trapped air in the matrix block. Because of the strong coupling between matrix imbibition and fracture flow, any phenomenon, such as trapped air, that alters the imbibition rate into the matrix blocks, will cause changes in the liquid saturation of the fractures (Zimmerman, *et al.*, in press), which in turn will affect the relative permeability of the fractures to both the liquid and gas phases. This in turn will affect the rate of transport of volatile radionuclides and volatile organic compounds in the gas phase. Whether or not these

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radionuclides can reach the water table or the atmosphere is a critical consideration for the judging the performance of the repository.

Current State of Understanding

The rate of water imbibition into matrix blocks can be predicted analytically, using Richards' equation along with the measured characteristic curves of the matrix block (Zimmerman and Bodvarsson, 1989; Zimmerman *et al.*, 1990). However, these calculations assume either that the air is "infinitely mobile," and is able to flow out of the matrix block by counterflow as the water imbibes in, or that the air is infinitely compressible. More rigorous calculations, which consider the coupled flow of both phases, can be made, but the results are highly dependent on the choice of boundary conditions, as well as on the choice of the parameters in the two (liquid, air) relative permeability functions. Kazemi *et. al.* (1992) have recently studied similar problems arising in oil and gas production from fractured reservoirs. An important conclusion, in the context of the workshop, was that the fracture-matrix transfer formation approach may work well for 'history matching' but generally does not correctly represent the physics of two-phase flow in fractured porous rock. Some calculations and experiments on soils indicate that air will be trapped inside the matrix blocks, and thereby impede the imbibition of water, that is, it will imbibe much more slowly than would be predicted by the Richards' equation analysis (Touma and Vauclin, 1986). On the other hand, some experiments on Yucca Mountain tuff (Kwicklis, personal communication) indicate that the air will not appreciably impede the flow of water into the block. Hence, the issue seems to be unsettled.

Research Needs

Carefully controlled laboratory imbibition experiments should be done on small cores of rock from the potential repository locations. The boundary conditions could be controlled to be either (a) fully-saturated with water under atmospheric pressure; (b) fully-saturated with water under a positive head excessive atmospheric; (c) nearly-saturated with water under a small suction, which would mimic the conditions during imbibition from a fracture carrying a pulse of rainwater. For comparison, imbibition tests could also be done on a core containing a "short-circuit" that would enable the air to escape readily. Each of these experiments should be modeled with a two-phase simulator such as TOUGH (Pruess, 1987), using measured physical properties as input parameters. Agreement between the experimental and numerical results would verify that all of the important governing physical processes are being accounted for.

Heat Transfer

Description of the Processes

The basic heat transfer processes are:

1. Conduction of heat through the solid matrix and stationary fluid phases
2. Convection of sensible and latent heat by fluids moving through and between fractures and matrix pores.

Two-phase flow can arise from evaporation (including boiling) and condensation in partially saturated rock, or from gas generation or exsolution in saturated rock. However, in the latter case, heat transfer effects would be minor. As in other problems involving two-phase flow in fractures, the basic processes are understood well enough to allow equations to be written and codes to be developed for their solution, but assumptions have to be made concerning mass and energy transfer rates between the fractures and the matrix. For example, if liquid is imbibed very rapidly from the fractures into the matrix, then the properties of the matrix will dominate advective liquid flow, and the details of the fracture network are not important -- only its effective permeability to gas. This assumption of local capillary equilibrium simplifies the mathematics, but may not correspond to reality. More complex formulations account for a finite rate of mass transfer between the two interpenetrating continua (Kazemi *et al.*, 1992). In principle, these are more realistic physically, but they require knowledge of the surface area per unit bulk volume which is effective for imbibition, the characteristic curves for the fractures and the matrix, and two-phase relative permeabilities for both media. These quantities are not measurable on a field scale, and must be inferred by modeling field-scale experiments, resulting in the usual difficulties of non-uniqueness.

Relation of Processes to Programmatic Issues

Yucca Mountain comprises a sequence of partially saturated, interbedded welded and non-welded tuffs with a wide range of matrix porosity and permeability and highly variable degrees of fracturing. A potential waste repository could produce radioactive decay heat per unit area initially several hundred times the natural heat flux. This thermal load has the potential for significant thermally-induced redistribution of water at scales ranging from inter-waste package distances to site scale, for thousands to tens of thousands of years. It could dominate the movement of both gas and liquid phases, and possibly also control transport of soluble and volatile radionuclides, for similar time periods. Potential beneficial effects include the possibility of preventing liquid water from contacting waste packages for extended periods, with concomitant reduction in the failure rate of the Engineered Barrier System (EBS), reduced availability of water for solution of radionuclides, and reduced liquid flux from the Engineered Barrier System to

the accessible environment. Benefits could be offset by heterogeneities which focus the increased liquid flux on a small number of packages. Saturated sites in other countries may not be as strongly affected by heat transfer phenomena under two-phase flow conditions. NAGRA and SKB will have much lower heat loads as the spent fuel to be emplaced will be stored in an interim storage for about 40 years to reduce residual heat production. Primary concern is the acceleration of gas production and possible breach of integrity of bentonite barrier by gas, in which case there could be two-phase flow in fractures, affecting rate of both gaseous and liquid-phase transport of radionuclides. Boiling is not expected to occur in deep saturated sites because of high fluid pressure and consequent high boiling temperatures, but gas exsolution and gas generation by chemical and microbiological activity could be increased. These could cause problems in maintaining repository integrity.

Current State of Understanding

Heat conduction is well understood. Thermal conductivity and heat capacity, or simply thermal diffusivity, are relatively easily measured in the laboratory, relatively unaffected by the presence or absence of fractures, and relatively uniform, varying only by factors of two to five within a given type of lithology for typical ranges of total porosity and water saturation (see Zimmerman, 1989). As indicated in the discussion above, difficulties arise in accounting precisely for the exchange of mass and energy between fractures and matrix components of a dual interpenetrating continuum. The assumption of local capillary equilibrium at Yucca Mountain does not seem capable of accounting for transient phenomena arising in episodic infiltration of meteoric water under isothermal conditions, and several investigators (Buscheck, Nitao, and Chesnut, 1991b; Zimmerman, 1994; Kazemi *et al.*, 1992) have studied the combinations of fracture and matrix properties for which the assumption must be replaced by an explicit representation of transient flow between these elements. It is customary in two-phase fluid flow / heat transfer problems to assume local thermal equilibrium between fluids in the fractures and fluids in the adjacent matrix. It is an interesting question whether or not this is justified under all conditions that must be considered in assessing repository performance. Is it necessary to consider the rate of heat transfer between fluid in a fracture and the surrounding matrix? The answer to this question could affect the probability of a hot waste package being contacted by water in a heterogeneously fractured medium. The main problem in successfully analyzing these phenomena is in the scaling of measurements and theoretical constructs from the scale of an individual matrix block to the scale of a computational block, and from the computational block scale to site scale, and in developing methods for estimating the resulting macroscopic parameters. For example, heat pipes are understood physically, but

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not in a geologic context. We simply do not know that controls the scale of heat pipes in natural geothermal systems, nor do we understand the interconnections from one part of a geothermal reservoir to another.

Research Needs

A clear need for the Yucca Mountain Project is the implementation of heater tests at different scales, preferably in strata which will be affected by a potential repository, or in closely analogous locations. These tests should be conducted under a wide range of heating conditions, generating sub-boiling as well as boiling conditions (Buscheck and Nitao, 1993a; Buscheck, Wilder, and Nitao, 1993). Such tests should be conducted as an iterative cycle of model predictions to design the experiment, actual conduction of the experiment, using models to analyze the results and determine possible mechanisms and associated parameter values consistent with the experiment, and then planning and conducting additional experiments to attempt to resolve ambiguities concerning mechanisms and scale effects. These should be closely coupled with study of potentially analogous situations in which similar processes are expected to occur, such as geothermal reservoirs and thermal oil recovery processes in fractured reservoirs. Lab scale tests involving matrix blocks containing one to a few fractures are also needed for the study of basic mechanisms.

Precipitation/Dissolution

Description of the Processes

Precipitation/dissolution is a phase change process between the solid phase (precipitate) and the dissolved aqueous phase. The equilibrium process is a function of the bulk rock mineralogy, aqueous and gas phase chemistry, and thermodynamic conditions. Nonequilibrium precipitation/dissolution will also depend on aqueous and gas phase flow and therefore is sensitive to fracture/matrix fluid flow properties.

Relation of Processes to Programmatic Issues

This phenomenon may be important for programmatic issues 1, 2, 4, 5, 6 and 7 due to the potential for precipitation/dissolution to alter the movement of gas and liquid by changing the spatial distribution of fluid flow properties.

Current State of Understanding

The state of knowledge concerning precipitation/dissolution phenomena and its impact on fracture/matrix flow processes is very limited. Reactions under thermodynamic equilibrium are relatively well understood and can be predicted with existing geochemical models. However, reaction kinetics are probably not known in sufficient detail to predict whether this phenomenon is important over the time scales of interest. In addition, the

coupling of fluid flow and precipitation/dissolution phenomena is beyond the capability of existing predictive models. For example, predictions of changing permeability field would require fundamenta' theoretical developments.

Research Needs

The primary research need is for scoping studies to determine if this phenomenon is expected to be important. Identification of chemical kinetics information is probably a critical element of these scoping studies. If the scoping studies determine that this is an important phenomenon, then development of models describing the impact of precipitation dissolution on fluid flow properties in coupled thermohydrologic-geochemical flow processes and subsequent configuatory experiments will be required.

Phase Changes

Description of the Processes

The phase change considered here is simply a thermodynamic process of changing liquid to vapor or vapor to liquid. The process occurs when nonequilibrium conditions exist between the liquid and vapor phase. The rate of phase change is dependent on the temperature, pressure, liquid water potential and vapor phase partial pressure (which is also dependent on temperatures and pressure) and also on the effective surface area. For example, dry air maybe forced into the rock by barometric pressure changes. The atmospheric air is dry relative to the rock gas, causing evaporation to occur in order to re-establish equilibrium. Since air flow occurs to a large extent through the fracture network, the phase change occurs mainly at the fracture surface and may be a major cause of deposition of minerals (fracture coatings).

Relation of Processes to Programmatic Issues

Phase change has an influence on most of the programmatic issues, in particular the transport of latent heat via evaporation and condensation.

Current State of Understanding

The basic thermodynamics are known on a microscale but must be simplified on a macroscale using approximate parameters. The importance of phase change on a site scale depends on the geometry of the system and the rate of heat build up and heat transfer.

Research Needs

To better understand the process and its importance several laboratory studies can be conducted:

1. The influence of water solubility and gas on boiling in the matrix block;
2. The influence of water removal from mineral structures on rock properties particularly on zeolites;

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3. the effect of deposition and dissolution on porosity, absolute permeability and characteristic curves;

4. the influence on the rate of temperature changes upon the process (i.e., does a rapid increase in temperature have a different effect on 1, 2 and 3 than a slow ramp-up of temperature?)

Vapor Flow Enhancement
Description of the Processes

Vapor flow enhancement is the process of increasing the conductivity of the vapor phase under a thermal gradient by condensing water on one side of a saturated pore throat and evaporating it at the other side. This process is controlled by the phase change process and the thermal gradient and asperity distribution and structure. Vapor flow enhancement becomes important at the flow restrictions in the fracture that lead to a discontinuous air phase. At lower liquid saturations a continuous air phase will short circuit the vapor flow enhancement pathway.

Relation of Processes to Programmatic Issues

The vapor flow enhancement issue is primarily related to programmatic issue #5, which deals with heat loading in a repository.

Current State of Understanding

The process of vapor flow enhancement is known to occur, but is poorly understood.

Research Needs

Laboratory tests and modeling need to be used to ascertain the importance of this phenomenon. Changing the characteristic curves to account for the process may be a simple technique to use in modeling studies.

Matrix Diffusion/Sorption
Description of the Processes

These processes concern the movement of gas or liquid-phase solute into the matrix adjacent to a fracture (matrix diffusion) or the adherence of solute on fracture walls and mineral coatings (sorption). These processes are important for radionuclide transport (such as gas-phase C^{14} transport through fractures) and provide potential mechanisms for impeding transport through partially saturated fractures.

Relation of Processes to Programmatic Issues

These processes principally affect the programmatic issues concerned with volatile radionuclide and VOC gas-phase transport (#2) and transport of liquid-phase radionuclides in liquid-and gas fast flow paths under unsaturated conditions (#4).

Current State of Understanding

The concepts of matrix diffusion and sorption are well understood, but their overall importance to geologic-repository performance needs to be investigated and assessed on a site-by-site basis considering site-specific conditions and performance requirements.

Research Needs

For a specific site, laboratory-scale experiments need to be performed using naturally fractured rock blocks to scope and evaluate matrix-diffusion processes, supplemented by column experiments using crushed rock to evaluate the sorptive properties. These experiments need to be performed for a sequence of controlled rock matrix and fracture saturations as well as different temperatures in cases where repository-induced heating of the rock mass may be significant. The experiments would need to consider liquid-phase and/or gas-phase transport, as appropriate, depending on the anticipated prevalence and importance of unsaturated fracture transport pathways.

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Report from Group 3: Complex Two-Phase Flow Processes in Fractures

After much discussion, the group decided to define the scope of their process discussion to embrace two-phase flow conditions which exhibited complex behavior, hence the name of this section. Four processes were singled out for examination:

- Fingering instabilities and "blob or bubble" flow (gravity or viscous driven)
- Pressure driven discontinuous flow
- Degassing/dissolution
- Ventilation/dryout

All of these processes were considered to have possible impacts on the six programmatic issues discussed above. In general, all of these processes involve the nonsteady movement of gas/water interfaces in fractures. These processes characteristically cause the development of complicated unsteady phase saturation structures within fractures. Since fracture properties such as the relative permeability, pressure/saturation relation and solute dispersivity depend on phase saturation structure, these processes have the potential to confound experiments conducted for model validation or characterization purposes. In addition, they can play major roles in the transport of gas and liquid to and from repositories within the two-phase zone.

Fingering instabilities and "blob/bubble" flow
Description of the Processes

Under conditions of two-phase flow, instability due to either viscous or gravity forces can cause a displacement interface between the gas and liquid to break into fingers. Where fingers occur, gas or liquid will move much further and with much less interaction with the surrounding matrix than otherwise assumed. For viscous fingering, the less viscous gas must be accelerated into the more viscous water. Such a situation may occur in the case of repositories in saturated zones where gas generation occurs. Gravity-driven fingering occurs when the less dense gas underlies the denser water in non-horizontal fractures. Downward infiltration of water through unsaturated fractures either from the surface or emanating from perched water in the subsurface may be dominated by fingering. Upward movement of gas/water interfaces in saturated repositories due to dryout during drift ventilation may also exhibit fingering. At low flow rates finger tips can detach and non-continuous blob flow may also occur for both of these cases. When a drift intersects a fracture in the saturated zone, if the height of the drift is greater than the difference between the water entry pressure head and the air entry pressure head, then water will flow out of

the bottom of the fracture and air will flow into the top of the fracture, rapidly creating a two-phase flow zone within the fracture.

Relation of Processes to Programmatic Issues

Viscous fingering is relevant programmatic issues: # 1, 2, 3:

1. Waste-generated gas causes pressure buildup and formation of a gas pocket, which is conducive to viscous fingering.
2. Viscous fingers create preferential flow paths for gas.
3. Characterization procedures will be affected by viscous fingering. Interpretation of field and laboratory tests will be impacted by these phenomena, particularly with regard to estimation of two-phase flow parameters.

Gravity-driven fingering is relevant programmatic issues: # 1, 2, 3, 4:

1. and 2. If fractures are non-horizontal then any gas generated by the repository that invades a fracture may move as a gravity-driven finger(s). Such fingers may move up rapidly and distribute gas phase throughout a large zone, possibly "breaching" the repository.
3. If gravity-driven fingering occurs during characterization tests and/or validation experiments, and it is not included in conceptual models used for interpreting results/determining properties, then the results may be misleading.
4. Gravity driven fingering of liquid water downward from the surface or in the subsurface into non-horizontal fractures can create persistent rapid flow paths for liquid water transport.

Current State of Understanding

What do we know?

Viscous and gravity-driven fingering has been studied in smooth walled fractures (Hele-Shaw cells) as an analog for two-phase flow in porous media. Linear stability analysis of the problem shows three factors to be influential in determining interfacial stability during a steady, one-dimensional, displacement of one fluid by another in a smooth walled fracture: the fluid viscosity difference, the fluid density difference, and the interfacial velocity (Saffman and Taylor, 1958). This result suggests viscous-driven instability for flow rates above a critical value and gravity-driven fingering when fluid is supplied to the fracture at less than the saturated permeability times the gravitational gradient along the fracture. Thus flows are seen to be stabilized or destabilized by viscosity and density differences for appropriate velocities. The role of capillarity at the interface restricts the unstable wavelengths to be above a minimum value.

Most research has concentrated on viscous-driven fingering in smooth walled fractures in the absence of gravity due to relevance to the production of oil and gas from porous media (see reviews by Saffman, 1986 and Homsy, 1989).

Gravity-driven fingering has been studied recently in rough-walled analog fractures for air/water systems (Nicholl *et al.*, 1992, 1993a,b). They demonstrated instability for the cases of redistribution following slug infiltration, inversion of density-stratified systems, and steady flow supplied at a rate less than the saturated permeability of the fracture. Instability was also demonstrated in a large vertical fracture in tuff during slug infiltration. Major findings of their research include:

1. Empirical relations for finger width and velocity were determined to be a function of flow rate and angle of the fracture with respect to gravity.

2. Linear stability theory was found to predict whether or not a system was unstable, but did not predict well the finger width, most likely because all fingers evolved from finite amplitude disturbances. This will likely be the case for most systems in nature as well.

3. Fingers showed unsteady behavior with drainage behind saturated finger tip and possibly chaotic pulsation at low flow rates.

4. Fingers persisted from infiltration event to infiltration event

5. Initial liquid content was shown to decrease the size and complexity of fingers instead of stabilizing the flow as is found in unsaturated porous media.

Experiments in Hele-Shaw cells demonstrate the formation of fingers from a saturated fracture when the aperture uniformly increases as expected near a drift due to mechanical effects (Watanabe *et al.*, 1987). In addition, the invasion of gas from below a saturated smooth walled fracture demonstrated the formation of a gravity-driven gas phase finger that moved upward.

Preliminary experiments in an analogue rough walled fracture have demonstrated gas phase fingering upward during dryout of a vertical fracture from below. Rapid fracture drainage can also occur in a fracture opened on its side such that the opening is of greater length than the difference of the air entry and water entry values for the fracture (Glass, personal communication).

Numerical simulations using a modified form of invasion percolation to include gravity and in-plane interfacial curvature have been fit to experimental behavior; however, critical tests of the model have yet to be performed (Glass, 1993).

What do we not know?

The effects of aperture distribution and structure within the fracture (heterogeneity) are not known. For gravity-driven fingering, experiments have only been conducted in statistically isotropic aperture fields formed by rough glass plates held in close contact (Nicholl *et al.*, 1992, 1993a,b) and one large (approx. 30 x 60 cm) natural fracture. No experiments on viscous fingering in rough walled fractures are known to the working group.

The effects of contact angle on the generation or suppression of fingering is not known. How fingers may coaless or disperse in fracture networks in natural formations is not known. How to incorporate understanding of fingering processes into larger scale effective media models is not known.

Research Needs

1.   Determine the effects of aperture field structure on gravity-driven and viscous fingering in fractures. Heterogeneity and anisotropy in the fracture aperture field can be expected to both stabilize and destabilize interfacial movement. It can be further hypothesized that if the correlation length of the fracture aperture structure is greater or less than the expected finger width then the heterogeneity may be significant or negligible, respectively. In order to examine this issue a series of systematic modeling and experimental studies are needed.   Modeling may use modified percolation simulators to explore quasi-static conditions. Physical experiments must be carried out in large casts of natural fractures and manufactured fractures where various spatial structures are milled into the fracture .

2.   Determine the effects of contact angle on gravity-driven and viscous fingering in fractures. Contact angle has not been explored in any previous work, and may either stabilize or destabilize a fluid displacement. In addition, one expects zones in fractured rock to have different contact angles within the fractures due to different mineralogy or histories.

3.   Determine whether effective media models can be defined for fractured rock that incorporate the effects of fingering for both the relative permeability within fractures and fracture/matrix interaction. It is possible that simple parameters such as cross-sectional area within the fracture where flow is occurring could be incorporated into effective media models to incorporate fingering to first order, and allow a more realistic evaluation in performance assessment.

Pressure-driven discontinuous flow:
Description of the Processes

Pressure-driven discontinuous flow has been observed in laboratory experiments in which both phases were injected to the fracture at constant flow rates, but exited the fracture at varying flow rates. The wetting phase (water) intermittently blocks the flow of the non-wetting phase (gas). The explanation is that the gas flow path has a critical throat (smallest aperture) at which the gas pressure is insufficient to prevent invasion of the wetting phase. When gas flow is blocked, the pressure builds up until it is great enough to displace the water and clear the path.

These observations may be artifacts of the test method. If the boundary condition were constant pressure instead of constant flow rate, would such intermittent blocking occur? Or does it result from the small size of the sample? Circumstantial evidence exists for such or similar phenomena in the field. During borehole testing at Wellenberg, gas flow rate varied widely (through a factor of ten) while pressure boundary conditions remained constant. At Stripa, liquid flow was spontaneously diverted between two outflow paths.

Relation of Processes to Programmatic Issues

The programmatic issues affected by this phenomenon include #1, integrity of the repository. Gas generated by corrosion, degradation, or radiolysis, must be allowed to escape. Blockage of the gas escape path could cause gas pressure to become too high. Another programmatic issue is #3, experimental artifacts. If the phenomenon does not occur in the field, then relative permeability curves based upon discontinuous flow data could be erroneous, and could decrease both the accuracy and precision of predictions. Programmatic issues #2 and #4 (gas and liquid transport) are affected through errors in prediction.

Current State of Understanding
What do we know?

We know that the intermittent blocking phenomenon occurs in the laboratory experiments conducted under flow-rate control. Certain observations of flow rates in the field suggest that the phenomenon may also occur naturally. Numerical simulations by Thunvik and B. aester (1990) have reproduced this effect in a fracture network.

What do we not know?

Does the same phenomenon occur in nature? Is the field experience cited above evidence for this phenomenon or for something else? If the laboratory experiments were conducted under pressure control instead of flow rate control, would intermittent blocking still occur? Does the phenomenon disappear at larger scale?

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Research Needs

Laboratory experiments with pressure control and larger sample size would clarify whether the phenomenon is only an artifact. Numerical simulations could be run to try to reproduce the phenomenon; this would aid understanding and could explain field observations. Additional measurements should also be done on a variety of fractures to determine the range of fracture properties that are to be expected at YM. Experiments should be done in such a way that they can be used to verify theories or conceptual models (e.g., local parallel plate approximation).

Degassing/Dissolution

Description of the Processes

Two-phase flow conditions due to degassing of gasses dissolved in the groundwater has been suggested as a possible mechanism responsible for the permeability reduction observed around a drift in the Stripa Mine (Olsson, 1992). In the Stripa Validation Drift experiment a reduction in inflow to the drift was observed compared to an array of boreholes. It was shown that the inflow reduction was caused by increased flow resistance near the drift wall. The largest flow reduction was observed in the small fractures ("good rock"). The flow reduction in the larger fractures was also significant although the relative flow reduction was smaller. The Stripa data also indicate a larger reduction of flow in the roof than in the floor (reliable data was obtained from a fracture zone only).

Gas released by a lowered pressure should be redissolved when pressures increase, e.g., after closure of the repository. Hence, gas dissolution will be of significance to predict the rate at which the repository resaturates.

The degassing and dissolution process is considered to be controlled by the following parameters:

- Gas solubility as a function of temperature and pressure,
- Partial gas pressure (gas contents) in the groundwater,
- Reaction rates for degassing and dissolution, and
- Fracture system geometry.

Relation of Processes to Programmatic Needs

Degassing/dissolution is relevant programmatic issues: #1,2,3,6

1. Gas generated in the repository could be transported from the repository either in the gas phase or as dissolved gas in the groundwater. The dissolution of gas released from the repository should be considered in predicting the amount of gas present and its transport away from the repository.

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2. Dissolution of released gas will impact (probably decrease) the transport of volatile species.

3. Depressurization causes the release of dissolved gas which may reduce liquid mobility. Redissolution may occur so slowly that the restriction to flow is maintained despite pressure build-up. This process changes the distribution of hydraulic conductivity around the drift and confounds the use of drift data to determine hydraulic properties of the undisturbed rock. It could also produce misleading data on flow distribution or channeling. Under certain circumstances degassing may also occur during borehole testing and if not considered properly will produce results not representative of conditions to be tested. Tests performed in drift boreholes to validate models can also be affected by degassing-dissolution phenomena.

6. Dissolution of trapped gas should be considered in predicting the resaturation rate of the buffer material, backfill, and host rock. The unsaturated zone determines the mass of oxygen present which may lead to corrosion reactions.

Current State of Understanding
What do we know?

The basic data for degassing/dissolution phenomena such as gas solubility as a function of temperature and pressure are known and can be found in tables. Data on gas content and composition of natural groundwater are scarce. Groundwater samplers for measuring gas contents in-situ are available and can be applied. The reaction kinetics of degassing/dissolution in highly-idealized systems, i.e., dissolving sphere in laminar flow field, are fairly well-characterized. It is also known that small bubbles will coalesce to form larger bubbles which decreases surface area to volume ratio which would tend to reduce reaction rates for dissolution compared to degassing.

For high dissolved gas concentrations, simple analytical models show degassing causes significant flow reduction in an effective porous medium. However, the model does not explain the magnitude of the flow reductions observed at Stripa. Studies of degassing and dissolution have also been performed in related fields where knowledge of relevance may be present. Examples of such areas are:

- Petroleum reservoirs where depressurization of reservoir drives volatile components out of solution, inducing two phase flow and reducing permeability of reservoir (mostly in porous media, e.g., Li and Yortsos, 1993)
- Power generation by boiling reactors - boiling, cavitation phenomena.
- Electro-chemistry; gas generation from electrodes.

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- Chemical engineering: Mass transfer in chemical reactors.

What do we not know?

The relative influence of degassing compared to mechanical effects due to drift excavation is not known. Degassing can be considered as a plausible hypothesis for observations made at Stripa, but the quantitative aspects of the phenomena are not understood. For example, this includes the expected magnitude of flow reduction and partial gas pressures at which the effect becomes important.

The influence of fracture geometry on degassing as well as dissolution is not known. Important questions are: What fracture parameters are important? What aperture distributions? What is its influence on reaction rates for degassing and dissolution. This is also related to the need to know the rules for phase occupancy with a discontinuous non-wetting phase. Does gas redissolve more slowly than it comes out of solution because the liquid/air interfacial area is reduced when gas occupies the larger pores. Is degassing influenced by the presence of colloids or small particles?

Characteristic curves for two-phase flow in fractures that address the presence of discontinuous non-wetting phase under degassing conditions are not known. Can bulk properties be defined for this phenomena, and if so, what are they?

Research Needs

To understand the mechanisms for degassing of groundwater and its influence on permeability, laboratory simulations should be performed on degassing effects in fractured rock. Such tests should include studies of the location of nucleation sites for gas bubbles, how the bubbles are transported from the nucleation sites, and where they get stuck in the fractures. Laboratory studies should also be performed to measure reaction rates in simplified geometries. It is also important to demonstrate the effect of degassing in-situ under relatively simple conditions. Test of degassing effects in boreholes would minimize effects of stress redistribution and induced fracturing caused by excavation.

Ventilation/dryout

Description of the Processes

Ventilation of repository drifts will lead to water evaporation and desaturation of the rock immediately surrounding the drift. Ventilation is also used to measure liquid flow to the drift in order to estimate hydraulic properties on a drift scale.

Relation of Processes to Programmatic Needs

Ventilation and subsequent dryout is relevant to programmatic issues #3 and #6.

#3: Enhanced moisture removal from the formation due to evaporation at the surface of a ventilated drift is an artifact which affects the (standard) interpretation of experiments conducted in the exploratory drift to determine undisturbed rock properties.

#6: Gas may be trapped during the desaturation-resaturation cycle induced by ventilation. This trapped gas contains oxygen. Oxidizing conditions in the near-field of a repository could affect canister corrosion rates and transport properties of radionuclides.

Current State Understanding
What do we know?
It is known from a series of experiments at the Grimsel Test site that ventilation creates an unsaturated zone around the drift which in these tests extended approximately 1.5 m from the drift wall. The experiments also showed that the total inflow (liquid and vapor) is affected while ventilating the drift.

What do we not know?
The mechanisms of transfer of moisture at the drift surface are not well understood. Of the parameters controlling this effect the diffusion coefficients (air and especially vapor) in porous media are not well known. It is not fully understood how data from ventilation tests should be interpreted in order to obtain values of the "undisturbed" hydraulic conductivity.

Research Needs
1. To better understand the process of drying, conceptual models need to be developed for the interpretation of data from ventilation experiments.
2. There is a need to develop test procedures to determine two-phase flow properties in-situ on a scale appropriate to the processes affecting programmatic issues.
3. Laboratory experiments are needed to determine vapor diffusion coefficients in porous media.

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Report from Group 4: Coupled Processes

Introduction

In order to understand this summary from the Coupled Processes Group, it is useful to understand the process by which this information was developed and organized. The group started by brainstorming a list of specific processes and other factors pertinent to coupled process impacts on multiphase flow in fractures. This brainstorm list was then refined by removing from consideration coupled processes or related factors that do not directly impact fluid flow. Then, with fluid flow as a common denominator, specific coupled processes were organized into a 3 x 3 matrix:

	Mechanical	Heat	Chemical
Mechanical	A	D	F
Heat	D	B	E
Chemical	F	E	C

Specific coupled processes in elements A, B, and C represent processes with flow-mechanical, flow-heat, and flow-chemical coupling respectively. Off diagonal elements D, E, and F represent processes with 3-way coupling. Following this Introduction, there are four sections describing groups of specific processes under the four categories of flow-mechanical, flow-heat, flow-chemical, and 3-way coupling.

In constructing this discussion of coupled processes, it is important to stress that only processes in which the coupling affects two-phase flow in fractures were included. Other coupled processes important to the performance of a repository are omitted either because flow is not directly involved or because the coupling is such that the flow is not affected. Transport of radionuclides falls into this category, despite its obvious importance to programmatic issues. Radionuclide transport is affected by heat though the temperature dependence of sorption coefficients and other transport properties, regardless of the flow conditions. Also radionuclide migration is controlled by flow via a "one-way" coupling, i.e. flow impacts transport but the presence of radionuclides has not direct influence on flow. However, other man-made materials such as cements may have a much larger

geochemical coupling impact on flow because the quantities are large and the potential for dissolution and precipitation is large. Chemical-mechanical flow coupling is not discussed because of insufficient expertise within the groups, but is known to be a significant effect in some cases.

In describing specific coupled processes below, a recurring theme in the transition from 'state of understanding' to 'research needs' is the need to address scaling up from laboratory time and space scales to repository time and space scales. One reason this transition proves challenging is the spatially heterogeneous nature of the geosphere and the temporally intermittent nature of geosphere boundary conditions. Although diffusive processes such as heat conduction and gas diffusion tend to diminish the effect of heterogeneities and intermittencies, coupled processes involving two-phase flow tend to be critically dependent on them, because of the nonlinearities inherent in the processes. Another important feature in many of the coupled processes is the interaction between the process occurring in the host rock and in the engineered design features of the repository.

Flow-Mechanical Coupling

In general terms, the coupling between 2-phase flow in fractures and mechanical processes is primarily through changes in hydrologic properties. Three forms of this coupling pertinent to repository issues were identified. Elevated gas pressures created by repository-generated gas cause fracture dilation or creation of new fractures. New fractures develop in response to excavation-related stress changes creating a disturbed rock zone in the near field. And finally, changes in the natural state of rock stress influences fracture apertures and, therefore, may impact hydrologic properties including 2-phase properties.

Process #1 - Fracturing driven by repository-generated gas

Description of the Processes

Gas-pressurization drives dilation of existing fractures or the creation of new fractures, thereby changing permeability, porosity, relative permeability, and capillary pressure.

Relation of Processes to Programmatic Issues

This process relates to Programmatic Issues #1 and #2. This process changes fluid flow to and from repository. This process may enhance water flow into repository and may provide new or enhanced pathways for transport of contaminants (volatile radionuclides or volatile organic compounds, VOCs) away from repository. This process is pertinent to repository programs where significant quantities of repository-generated gas may be created (SKB, NAGRA, and WIPP).

Current State of Understanding

What do we know?:

Know that in general permeability and porosity increase as fractures dilate, and that relative permeability and capillary pressure change as well. Currently have limited capabilities for quantifying the relationship between gas pressure and changes in permeability and porosity. Field scale measurement techniques are under development to get permeability and local (near-borehole) aperture changes as a function of fluid pressure.

What do we not know?

Currently, we have very little knowledge of how to quantify the relationship between fluid pressure and two-phase properties. Techniques for measuring such relationships for single fractures in the laboratory are currently in the early stages of development.

Research Needs

- Continue development of field and laboratory techniques for quantifying permeability changes as a function of fluid pressure.
- Continue development of laboratory techniques for quantifying the relation between fluid pressures and changes in 2-phase properties as function of fluid pressure.
- Develop mechanistic models to incorporate and extend laboratory and field measurements of coupling relationships so that these relationships can be incorporated into larger scale simulations.

Process #2 - Development of near-field disturbed rock zone

Description of the Processes

Excavation-related stress changes drive creation of a disturbed rock zone with discrete fractures, micro fractures, and/or dilation of pores.

Relation of Processes to Programmatic Issues

This process relates to Programmatic Issues #1, #2 and #4. This disturbed rock zone creates new fluid flow paths, increases near-field porosity, and may develop two-phase flow conditions due to evaporation and/or gas exsolution. New flow paths may enhance migration of volatile species through the near-field to other far-field transport pathways. Near field increases in porosity may increase near-field storage volume for storage of repository-generated gas. Two-phase flow conditions near the repository creates complexities in the design and interpretation of hydrologic tests that are intended to characterize undisturbed rock properties and flow processes (Issues #3). This process is pertinent to YMP, WIPP, SKB, and NAGRA

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Current State of Understanding

What do we know?

We know that disturbed rock zones develop around excavations in all rock types, including salt. Two-phase, partially saturated conditions commonly develop within the disturbed rock zone. Increased permeability in disturbed rock zone is also commonly measurable.

What do we not know?

We currently do not have rigorous models that can predict the long-term, time-dependent changes in flow properties within the disturbed rock zone. Currently have limited ability to measure degree of saturation and changes in saturation within the disturbed rock zone.

Research Needs

- Develop techniques for measuring porosity and saturation state within disturbed rock zone.
- Develop rigorous models that can predict the long-term, time-dependent changes in flow properties within the disturbed rock zone.
- Need a better understanding of two-phase flow properties in fractures.

Process #3 - Changes in natural state of rock stress influences fracture apertures and hydrologic properties

Description of the Processes

Changes in natural stress state impacts fracture formation, growth, and apertures, and therefore hydrologic properties. Several repository sites are in tectonically active regions (e.g., Yucca Mountain is in a rift zone, Switzerland is in a compressive zone).

Relation of Processes to Programmatic Issues

This process relates to Programmatic Issues #2 and #4. New flow paths may enhance migration of volatile radionuclides, as well as providing fast paths for both liquid and gas flow.

Current State of Understanding

The formation and growth of fractures in response to in situ stress is well known for idealized systems (e.g., initially uniform medium, non-interacting cracks). Interpretations of the evolution of natural stress can be made by identifying and time-ordering different fracture sets in the field.

Research Needs

The long time scales on which tectonic changes occur makes this coupled process ill-suited to laboratory experiment. However, modeling combined with fracture mapping in the field may provide insight into the effects of changes in tectonic stress. Fracture genesis methods need to be extended to three-dimensions and to include heterogeneties and crack interaction.

Flow-Heat Coupling

Coupling between 2-phase flow in fractures and heat involves various ways in which heat acts as a driving force for fluid flow. A second manner in which flow and heat are coupled is through heat-driven changes in hydrologic properties. This coupling is usually characterized by heat-induced mechanical changes to fracture apertures and/or the creation of new fractures. Because this is actually a three-way coupling between flow, heat, and mechanical processes, it is discussed in a later section. Fluid (gas or liquid) flow is driven by density gradients resulting from temperature gradients. Gas-phase advection is driven by total pressure gradients caused by vaporization or condensation. Water vapor diffusion is driven by vapor pressure gradients resulting from temperature gradients.

Process #1 - Buoyancy driven flow
Description of the Processes

Fluid (gas or liquid) flow is driven by density gradients resulting from temperature gradients. This process can occur with or without phase change. Phase change effects include drying of regions due to evaporation, buoyant movement of moist air, and wetting in cooler regions due to condensation (possibly resulting in condensate drainage in fractures), and extremely efficient heat transfer due to latent heat flow (heat pipe) (Nitao, 1988; Buscheck and Nitao, 1993a).

Relation of Processes to Programmatic Issues

This process impacts Programmatic Issues #2, #4, and #5. Buoyancy driven gas-phase flow can transport volatile radionuclides, particularly in fractures (Issue #2). Condensate drainage can provide liquid water for transport of radionuclides through fast flow paths (Issue #4). Buoyancy driven fluid flow may strongly affect the flow environment near the repository (Issue #5) (Buscheck and Nitao, 1993a). This issue is pertinent to YMP and both SKB and NAGRA during resaturation of the backfill surrounding waste canisters.

Current State of Understanding
What do we know?

Buoyancy driven gas-phase flow depends on three factors: temperature gradient, bulk permeability, and availability of liquid water. In theory, three regimes of buoyant gas-phase flow exist, which depend on these three factors (Buscheck and Nitao, 1993a). These flow regimes are characterized as follows:

1. Buoyant gas-phase flow does not significantly affect saturation or temperature distributions;
2. Buoyant gas-phase flow significantly affects saturation distribution but not the temperature distribution.;
3. Buoyant gas-phase flow affects both saturation and temperature distribution.

Modeling for YMP suggests that buoyant flow is strongly affected by vertically layered bulk permeability distributions (Buscheck and Nitao, 1993a). Modeling for YMP also suggests that if buoyancy driven flow is significant, its effects will last for tens of thousands of years for YMP (Buscheck and Nitao, 1993a). Such flow may be active for much shorter periods of time for SKB and NAGRA. Large scale gravity-driven heat pipes have been inferred from observations of two-phase geothermal systems (Pruess, 1985).

What do we not know?

We do not know how the spatial distribution of properties affects buoyant flow. We do understand the significance of fracture/matrix interaction on drying and wetting behavior. Conditions which can give rise to non-equilibrium condensate drainage are not well defined. We do not know whether drying causes a build-up of salts near fracture walls.

Research Needs

- A better understanding of connected fracture permeability and other relevant site properties that provide the basic flow framework in which coupled flow-heat processes occur is needed.
- Experimental observation of heat-driven flow processes is needed under laboratory conditions where direct observations, quantitative measurements, and systematic variation of controlling parameters are possible.
- Larger scale in-situ heater tests that develop 2-phase flow conditions at an adequately large scale that heat-driven processes can become fully developed and can be observed through indirect measurements (Buscheck, Wilder, and Nitao, 1993).

- Both laboratory and larger scale experiments should be carried in close collaboration with numerical simulation studies. Also, conducting focused laboratory work in conjunction with larger scale experiments may provide an important basis for interpretation of the larger scale experiments.

Process #2 - Gas-phase advection driven by total pressure gradients

Description of the Processes

Gas-phase advection is driven by total pressure gradients caused by vaporization or condensation.

Relation of Processes to Problematic Issues

This affects issues #2, #4, and #5. The interaction of heat-driven flow and gas advection influence the transport of volatile radionuclides (Programmatic Issue #2). Condensation may provide a source of water for fast paths in fractures (Programmatic Issue #4). Gas advection and condensation also impacts composition and flow rates of gas and liquid around the waste package (Programmatic Issue #5).

Current State of Understanding

What do we know?

Modeling for YMP suggests that rock dry-out rate is linearly dependent on thermal loading (Buscheck and Nitao, 1992, 1993b) and that pressure gradients caused by boiling suppresses buoyancy driven flow (Buscheck and Nitao, 1993a). This process increases with thermal load. This process can result in the development of heat pipes, which may have dramatic effects on near-canister conditions, including limiting temperature increase to boiling temperature ($100°$ C at YMP), maintaining moisture content, and purging non-condensable gases (which may impact canister corrosion) (Pruess et al., 1990; Doughty and Pruess, 1992).

What do we not know?

The impact of the distribution of site properties (heterogeneities) and infiltration on gas phase advection processes is not well understood. The behavior of gas phase advection under low saturation conditions is not clearly understood.

Research Needs

While insights on flow-heat coupling related to gas advection have grown from numerical simulation studies, very little experimental work has been done to confirm the expected behavior. In-situ heater tests, block tests, and laboratory tests that examine the interactions of buoyancy-driven flow, pressure-driven advection, and water vapor diffusion are needed as well as experimental and numerical studies to determine the impact of heterogeneities on pressure-driven gas advection. The conditions under which

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heterogeneities accentuate flow and under what conditions heterogeneities damp flow needs to be examined.

Process #3 - Water vapor diffusion driven by vapor pressure gradients

Description of the Processes

Water vapor diffusion is driven by vapor pressure gradients resulting from temperature gradients.

Relation of Processes to Programmatic Issues

This process impacts Programmatic Issues #2, #4, and #5. This process occurs in conjunction with buoyancy-driven flow and pressure-driven gas advection, thereby affecting transport of volatile radionuclides (Programmatic Issue #2) and fast pathway transport of radionuclides dissolved in water (Programmatic Issue #4). In addition, depending on its magnitude, this process may impact the amount of air (oxygen) present near waste packages affecting oxidation corrosion (Programmatic Issue #5).

Current State of Understanding

What do we know?

The relative significance of this process increases with decreasing bulk permeability (i.e. diffusion of water vapor becomes comparable to convection at low bulk permeabilities). The relative importance of diffusive transport increases with decreasing thermal load.

What we do not know?

The binary water-vapor/air diffusion coefficient is not well quantified in fractured rock environments. Pore-scale phase change effects may greatly increase the vapor diffusion coefficient.

Research needs

There is a need to quantify binary diffusion coefficients in fractured rock through laboratory and field testing.

Flow-Chemical Coupling

Coupling between flow and chemical processes is primarily through changes in hydrologic processes due to dissolution and/or precipitation. This section focuses on changes that occur under isothermal conditions. The following section then addresses the additional coupling that comes into play under nonisothermal conditions.

Process #1- Fluid-rock interactions resulting in dissolution and/or precipitation

Description of the Processes

Fluid-rock interactions can result in dissolution/precipitation reactions that cause spatial and temporal variations in the hydrologic properties of the fractures. In addition, fluid exchange between fractures and matrix could be inhibited or enhanced by the creation or removal of fracture coatings.

Relation of Processes to Programmatic Issues

Fluid-rock interactions also represent an important mechanism for radionuclide transport retardation. These processes impact the liquid water fast flow paths by plugging previously flowing fractures, opening of previously clogged fractures, or changing fracture-matrix interactions by clogging or opening the matrix pore space adjacent to a transmissive fracture (Programmatic Issue #4).

Current State of Knowledge

What do we know?

To properly model rock-water interactions, both equilibrium thermodynamic properties and kinetic rate coefficients are needed. These parameters are usually strongly temperature dependent. Thermodynamic data are known for many simple rock-water reactions for standard temperature and pressure conditions. Computer codes such as EQ3/6 (Wolery, 1970) calculate rock-water interactions for such systems.

The THCC family of computer codes couple chemical reactions with flow, heat, and mass transport in a 2-D saturated homogenous system (Carnahan, 1986). One of those codes, (THC VP) accounts for changes in porosity due to precipitation reactions (Carnahan, 1990).

Studies of fracture mineral coatings have been carried out at Yucca Mountain to identify the types of coatings and their distribution. Fracture mineral coatings have also been studied by NAGRA and SKB.

What we do not know?

While the thermodynamic data base for relatively pure rock-water interactions is fairly good, data for more complex systems pertinent to potential repository conditions is lacking. Rate data is much less well known as well, especially at elevated temperatures. Computer codes such as EQ3/6 calculate rock-water interactions, but do not include flow or transport. Flow and transport models capable of simulating two-phase flow in fractures generally include no or greatly simplified chemical reactions. The extent to which fracture coatings inhibit matrix imbibition is also unknown.

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Research Needs

Thermodynamic and rate data are needed for repository conditions. The rock-water interactions as modeled by computer codes such as EQ3/6 are too complex to be incorporated into flow and transport codes in their entirety. The task of extracting key reactions from EQ3/6 for inclusion in a multi-phase flow and transport code is a considerable effort, but an important one. Probably this should be an iterative process, involving repeated use of EQ3/6 for a variety of conditions suggested by flow and transport modeling. It is not known if this is a viable approach for realistic field-scale modeling, and consideration should be given to establishing an alternate approach entirely . Codes such as THCC should be further developed to enable modeling two-phase flow that is fully coupled to chemical reactions.

Site-specific laboratory studies could be carried out to test the impact of matrix coatings on imbibition. Site characterization efforts should continue to obtain additional data on fracture coatings, integrating this data with site-scale flow models to check their consistency.

Process #2: Gas Generation

Description of the Processes

Microbial degradation of cellulosie material in some waste types (e.g., WIPP, NAGRA, SKB) can generate significant quantities of gas. Corrosion of the cannisters themselves may also generate gas. If this gas migrates through the engineered barrier to the geosphere, it can significantly affect the hydrologic processes by introducing a free gas phase.

Relation of Processes to Programmatic Issues

Generation of large quantities of gas may change fluid flow to and from the repository (Issue #1). This may inhibit or enhance water flow into the repository; may enhance transport of contaminant (volatile radionuclides or VOCs) away from the repository (Issue #2). This issue is pertinent to WIPP, SKB, and NAGRA.

Current State of Understanding

What do we know?

Laboratory experiments have been used to characterize gas generation by microbial activity and provide a basis for estimating gas generation rates.

Research Needs

Detailed understanding of microbial activity over extended periods of time is yet to be achieved. Impacts of microbial activity on water budget (consumes water vs. produces water) are not well known.

Flow-Heat-Mechanical Coupling

Description of the Processes

Heat-induced stress change induces changes in fracture aperture and can add fractures, thus modifying flow properties.

Relation of Processes to Programmatic Issues

Issue #4 is impacted because fast paths may be enhanced or restricted as fracture aperture changes. Issue #5 is relevant because heat is the source of aperture changes.

Current State of Knowledge

Modeling studies using the coupled thermo-hydro-mechanical model ROCMAS have been done for a heat-generating repository in a fractured/porous medium under saturated conditions, which suggest fracture aperture does change appreciably in response to thermal loading (Noorishad et al., 1984; Noorishad and Tsang, 1991).

Research Needs

Application of models such as ROCMAS to two-phase conditions (both unsaturated zone or below-water-table two-phase conditions created by gas generation) is needed. Such studies can identify the key parameters to measure in the laboratory or field. Effects on geologic media should be considered in conjunction with effects on engineered components. For example, heating causes rock to expand, which at first should restrict fracture aperture. Further expansion could cause disintegration of rocks, creating new fractures, but this effect could be precluded by disintegration of the drift itself, alleviating pressures in the rock.

Flow-Heat-Chemical Coupling

Rock-water interactions (precipitation and dissolution) are usually strongly temperature-dependent; these reactions can reduce or enhance fracture aperture, thus modifying flow. Microbial activity is also strongly temperature dependent. Thus, in a sense, all the chemical-flow couplings are also coupled to heat flow, so some of the needs for research given below are widely applicable. However the example given below discusses a more direct coupling in which *changes* in thermal regime impact chemical reactions.

Description of the Processes

Flow of water through variable temperature regimes results in changing fluid temperature, which in turn causes the fluid to become undersaturated or supersaturated with respect to certain rock minerals. Phase change can also lead to undersaturation or supersaturation. Undersaturation or supersaturation may cause dissolution or precipitation, respectively, leading to enlargement or restriction of fracture flow paths.

Relation of Processes to Programmatic Issues

Programmatic issue #4 is impacted by this coupling because these processes could play an important role on the permeability of fractures, which in turn controls the large scale flow and heat transport mechanisms. In the same way, issue #2 is also impacted. Finally, this coupling could impact the heat transfer process (issue #5) through the complex interplay between rock-water interactions, fracture flow properties, and heat transfer.

Current State of Understanding

To properly model rock-water interactions, both equilibrium thermodynamic properties and kinetic rate coefficients are needed. These parameters are strongly temperature dependent. Thermodynamic data are known for many rock-water reactions for standard temperature and pressure conditions, however these are much different than potential repository conditions. Rate data is generally less well known than equilibrium data, especially at elevated temperatures. Computer codes such as EQ3/6 calculate rock-water interactions, but do not include flow or transport. Flow and transport models capable of simulating two-phase flow in fractures generally include no or vastly simplified chemical reactions. Modeling studies including fluid flow, heat flow, and silica dissolution, transport, and precipitation (assuming equilibrium conditions) in a liquid-saturated fractured medium indicated that silica redistribution does not have a sizable effect on repository conditions (Verma and Pruess, 1988), however the incorporation of two-phase flow effects and reaction kinetics may greatly alter this conclusion. Most of the TNCC codes include temperature effects (e.g., Carnahan, 1992), but are limited to single-phase liquid conditions.

Research Needs

Thermodynamic and rate data are needed for repository conditions. The rock-water interactions as modeled by computer codes such as EQ3/6 are too complex to be incorporated into flow and transport codes in their entirety. The task of extracting key reactions from EQ3/6 for inclusion in a multi-phase flow and transport code is a considerable effort, but an important one. Probably this should be an iterative process, involving repeated use of EQ3/6 for a variety of conditions suggested by flow and transport modeling. It is not known if this is a viable approach for realistic field-scale modeling, and consideration should be given to establishing an alternate approach entirely.

Codes such as THCC should be further developed to enable modeling two-phase non-isothermal flow. Heater tests provide the possibility to study heat/chemical processes. Heat/chemical coupling can be studied qualitatively by doing a post-mortem examination of the fracture mineral distribution.

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APPENDIX A

Agenda

Two-Phase Flow Workshop

November 3-4, 1993

Berkeley City Club, Berkeley, California

A G E N D A

Wednesday, November 3th

8:30   Welcome and discussion of the purpose of the conference (Jane Long, Peter Davies)
- Define state-of-the-art
- Define research needs
- Working group concept
- Handling disagreements
- White paper product

8:45   Introduction of participants
- who you are, where you work, your scientific focus, mention any key issue you want to see discussed

9:00   Key problems and issues
- Swedish perspective - *(Olle Olsson)*
- Swiss perspective - *(Piet Zuidema)*
- US Yucca Mtn. perspective - *(G. Bodvarsson)*

- Wipp perspective- *(Peter Davies)*

9:40   break

9:45   Keynote on the state-of-the-art modeling perspective *(Karsten Pruess)*

10:15   Discussion

10:30   Keynote on the state-of-the-art laboratory perspective *(Bob Glass)*

11:00   Discussion

11:15   Keynote on the state-of-the-art field experiment perspective *(Ed Kwicklis)*

11:45   Discussion

12:00   lunch

1:00   5 to10 minute participant presentations (Note: each speaker is limited to one bulleted viewgraph and two illustrations)
- What two-phase flow processes are you working on
- What is your approach
- Evaluate the state of understanding
- Point to research needs relevant to repository performance

4:30   Organization of working groups to define consensus on the state-of-the-art and research needs
- reach consensus on the key processes of interest

5:30   Adjourn

6:30   Conference Dinner- U.C. Men's Faculty Club

8:30   Groups meet to
- finalize the list of key processes
- plan activities for the next day

Possible key processes include:

- Basic flow processes
  - wetting/draining and sequential wetting and draining effects
  - threshold pressure effects in low permeability media
  - geometric control
  - transport (incl. colloids)
  - processes and conditions leading to strongly preferential flow
- Matrix/fracture interactions
  - hydrophobic conditions
- Dynamic (or dynamical) vs. equilibrium behavior
  - fingering instabilities
  - drift processes
  - drying/evaporation
  - degassing/dissolution
  - non-continuous flow
- Coupled Processes
  - flow coupled to heat
  - chemical effects
  - stress effects

Thursday, November 4th

8:30   Summary of previous day, review assignments

8:45   Working groups meet to prepare consensus reports

Should include what is known about the cluster of key processes
What are the unknowns, what are the needs?

12:00   Working Lunch: Working groups report on their progress

1:00   Group discussion to evaluate progress, possibly reshuffle groups

2:00   Working groups prepare statement on how to address the needs in terms of
- lab—qualification/quantification of relevant phenomena
- field—sufficiently constrained experiments
- theoretical—interaction of complex processes and complex geometry
- numerical efforts—including new processes

4:00   Reconvene, summation

5:00   Adjourn

Friday, November 5th

Conference organizers and key note speakers meet to finalize white paper.

APPENDIX B

List of Participants

Organizers
Peter Davies, Jane Long, Olle Olsson, Piet Zuidema

Keynote Speakers
Gudmundur Bodvarsson, Robert Glass, Karsten Pruess, Ed Kwicklis

Friday Writers
Peter Davies, Jane Long, Olle Olsson, Piet Zuidema, Robert Glass, Karsten Pruess, Ed Kwicklis, Gudmundur Bodvarsson, Christine Doughty

Observers
Parvis Montazar, Claudia Newbury, Jiamin Wan

Participants:

Lawrence Berkeley Laboratory:	Bo Bodvarsson
	Christine Doughty
	Stefan Finsterle
	Jil Geller
	Kenzi Karasaki
	Peter Persoff
	Karsten Pruess
	Bob Zimmerman
Sandia National Laboratories:	Peter Davies
	Rick Beauheim
	Bob Glass
	Cliff Ho
Lawrence Livermore National Laboratory:	Tom Buscheck
	Dwayne Chesnut
U.S. Department of Energy:	Claudia Newberry
Los Alamos National Laboratory: .	Bruce Robinson
United States Geological Survey:	Al Flint
	Ed Kwicklis
	Dwight Hoxie
Nagra:	Piet Zuidema
	Rainer Senger
	Gerhard Mayer
Power Reactor and Nuclear Fuel Development: Corporation	KunioWatanabe Saitama University
INTERA:	SriKantra Mishra

M&O Performance Assessment: James Houseworth

SKB: Olle Olsson
                                   Georgia Destouni

Observers: Parvis Montazer
                                   Jiamin Wan