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Brine Flow in Heated Geologic Salt

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Abstract

This report is a summary of the physical processes, primary governing equations, solution approaches, and historic testing related to brine migration in geologic salt. Although most information presented in this report is not new, we synthesize a large amount of material scattered across dozens of laboratory reports, journal papers, conference proceedings, and textbooks.

We present a mathematical description of the governing brine flow mechanisms in geologic salt. We outline the general coupled thermal, multi-phase hydrologic, and mechanical processes. We derive these processes' governing equations, which can be used to predict brine flow. These equations are valid under a wide variety of conditions applicable to radioactive waste disposal in rooms and boreholes excavated into geologic salt.

We focus on the development of the governing equations with the intent to solve them analytically or in a simplified numerical manner, although we briefly summarize some available fully coupled three-dimensional numerical models and some historic modeling results. We non-dimensionalize the governing equations, and make some statements about importance of terms in the governing equations for physically plausible ranges of material property values.

We summarize both in situ and laboratory brine migration testing in intact geologic salt, primarily focusing on tests performed under heated conditions relevant to high-level waste disposal. Supporting material is presented in appendices on relevant aspects of laboratory water content determination for bedded salt, the nature and evolution of the disturbed rock zone, and geologic salt permeability testing.

In the final summary chapter, we provide a narrative description of the processes controlling both isothermal and heated brine inflow to excavations in geologic salt. Based upon our review, we recommend several potential in situ and laboratory tests, which could be conducted to increase understanding, parametrize numerical models, and confirm the importance of competing physical processes.

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Nomenclature

AEC US Atomic Energy Commission (pre-1975 predecessor to ERDA)

BSEP Brine Sampling and Evaluation Program (WIPP brine monitoring program 1982–1993)

CODE BRIGHT COupled DEformation, BRIne, Gas and Heat Transport (Universitat Politècnica de Catalunya finite-element numerical model)

DOE US Department of Energy (cabinet-level successor to ERDA)

DRZ Disturbed Rock Zone (US synonym for EDZ)

ERDA US Energy Research & Development Agency (post-AEC, pre-1977 predecessor to DOE)

EDZ Excavation Damaged Zone (European synonym for DRZ)

FEHM Finite Element Heat and Mass transfer (LANL numerical model)

FLAC3D Fast Lagrangian Analysis of Continua in 3D (geomechanical model by Itasca Consulting Group)

LANL Los Alamos National Laboratory (Los Alamos, NM)

LBL Lawrence Berkeley National Laboratory (Berkeley, CA)

MB139 Marker Bed 139 (0.9-m thick anhydrite/clay unit below WIPP repository horizon)

MCC Mississippi Chemical Company (Former potash mine near Carlsbad, NM)

ONWI Office of Nuclear Waste Isolation (run by Battelle Memorial Institute – Columbus, OH)

ORNL Oak Ridge National Laboratory (Oak Ridge, TN)

SNL Sandia National Laboratories (Albuquerque, NM)

THM Thermal-Hydrologic-Mechanical coupled modeling

THMC Thermal-Hydrologic-Mechanical-Chemical coupled modeling

TGA ThermoGravimetric Analysis (Monitoring mass during heating to estimate water content).

TOUGH2 Transport Of Unsaturated Groundwater and Heat, version 2 (LBL integrated finite-difference numerical model)

WIPP Waste Isolation Pilot Plant (DOE transuranic waste repository near Carlsbad, NM)

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Chapter 1

Introduction

Salt is considered a primary medium for radioactive waste disposal in the United States and Germany. In 1955 the US Atomic Energy Commission (AEC) convened an expert panel to recommend best practices for radioactive waste disposal from the growing US nuclear weapons and power industries (Hess et al., 1957). The primary panel recommendation was to investigate direct disposal of liquid reprocessing waste in salt cavities. Oak Ridge National Laboratory conducted field liquid waste disposal tests using rectangular pits mined into the floor of the Carey Salt Mine (Morgan, 1959). Complications from these tests related to salt cavity stability and off-gas containment led to the recommendation for disposal of solidified waste (Lomenick, 1996, §2.2.2). Currently, most US heat-generating radioactive waste is solid spent fuel or vitrified glass logs. Disposal of solid radioactive wastes may involve placing casks or canisters in boreholes or rooms mined into stable geologic salt deposits. Both the US and Germany have extensive geologic salt deposits, with some in suitable areas for waste disposal (Johnson and Gonzales, 1978; Isherwood, 1981). In the US, WIPP is the only operational deep geologic salt radioactive waste repository, but several other candidate salt sites have been investigated, including Palo Duro Basin (Texas), Lyons (Kansas), Paradox Basin (Utah), and several Gulf Coast salt domes (Lomenick, 1996, Appendix D).

Salt, at proposed repository depths (less than 1 km depth) and thermal loads (hundreds of Watts to a few kW per canister), is a somewhat unique repository host medium because the relative importance of thermal, hydraulic, chemical, and mechanical processes requires no one portion be completely ignored. Even at isothermal conditions, brine flow in salt is coupled with salt geomechanical behavior. Clay, granite, and shale repositories or deep borehole disposal concepts do not typically necessitate fully coupled simulation to determine the quantity or fate of water transport. Salt is considered a candidate medium for waste disposal because it has the unique benefit of self-healing behavior (i.e., creep) under typical repository conditions.

In this report we summarize the observed physical phenomena, inferred governing mathematics, analytical and numerical solutions, and historical laboratory and field experiments related to brine inflow in heated geologic salt. The topic is of central importance to understand and predict the complications associated with brine flow in salt surrounding radioactive waste (e.g., Used Fuel Disposition Campaign (2012, Appendix B)). We present the governing equations, setting the stage to solve or understand the equations using simplified solution techniques, rather than proceeding immediately to a multi-physics finite element formulation to solve the coupled THMC flow problem. This approach has not been covered in the literature. Little has been done since McTigue

(1986, 1990, 1993) developed analytical thermoporoelasticity solutions for heated and isothermal brine inflow. With this report, we begin to address this perceived gap.

We derive the governing equations for brine migration in intact geologic salt. We derive the equations for single-phase brine flow in a similar but more general form to the thermoporoelastic approach taken by McTigue (1986, 1990). Due to the inherently coupled, and often non-linear nature of the governing equations, most researchers immediately proceed to use numerical models to match observed data and make predictions. It is possible and sometimes necessary to consider many non-linear competing effects in a large-scale three-dimensional simulation. The computational resources and modeler time required to set up and simulate fully coupled three-dimensional THMC models often prohibits their use for numerical exploration and hypothesis testing. Simplified solutions have definite limitations, but we feel they encourage investigation of parameter uncertainty and physical insight. In this report we intend to lay the foundation for approximate analytical, semi-analytical, and numerical solutions to the coupled brine flow problems in geologic salt. Starting from previous simplified forms, or considering new simplifications of the general equations, we can approximate the natural system with sufficient complexity to capture the essence of observed physical behavior. We show how historically derived analytical solutions are obtained as simplifications to the governing equations derived here.

Brine movement in crushed salt is governed by the same physical processes and equations as brine movement in intact salt. The main difference is crushed salt's increased porosity and permeability compared to intact or even highly disturbed salt near excavations. Free convection or buoyancy-driven gas and vapor flow is typically much more important in crushed salt, than intact salt. Free convection is a non-linear process, and therefore it is difficult to derive analytic or simplified solutions to these type problems. Despite this dichotomy between mostly saturated brine flow in intact salt and free vapor convection in crushed salt, it is still very important to understand brine flow in intact salt, as it is the ultimate brine source in a sealed geologic repository.

Brine in Salt

Figure 1.1 illustrates two of the four primary water forms in bedded rock salt, intergranular and intragranular brine in pure halite. Figure 1.2 shows a typical non-salt anhydrite interval from the bedded Salado Formation at the Waste Isolation Pilot Plant (WIPP). The four brine types we consider are:

- Intracrystalline brine inclusions in salt (loosely called “negative crystals” – Figure 1.1);
- Intercrystalline (i.e., grain-boundary or pore) fluids (Figure 1.1);
- Waters of hydration bound to hydrous minerals disseminated through or associated with salt, including:
 - polyhalite $\text{Ca}_2\text{K}_2\text{Mg}(\text{SO}_4)_3 \cdot 2(\text{H}_2\text{O})$,

Figure 1.1. Idealized intracrystalline brine inclusions and inter-crystalline pore fluids (brine and gas) in salt (Olivella et al., 1995)

Figure 1.2. Idealized lithology of a typical non-salt component of bedded salt (MB139) at WIPP (Borns, 1985)

- carnallite $\text{KMgCl}_3 \cdot 6(\text{H}_2\text{O})$,
 - kainite $\text{KMg}[\text{Cl}|\text{SO}_4] \cdot 3(\text{H}_2\text{O})$, and
 - hydrated smectite clays (e.g., bentonite or montmorillonite).
- Pore water in non-salt layers commonly found in geologic salt (e.g., anhydrite, mudstone or shale, and clay – Figure 1.2).

Early laboratory permeability testing in the 1950s showed porous medium flow occurred through salt samples from the Grand Saline salt mine (Reynolds and Gloyne, 1960; Gloyne and Reynolds, 1961). After this, most pre-1980 research on brine movement in salt focused on intracrystalline fluid inclusions.

Although intracrystalline brine inclusions are often volumetrically the largest brine component in relatively pure bedded salt (see Appendix A), the significance of brine flow through connected intergranular porosity has been shown in numerous field and laboratory studies. The surge in brine inclusion research was fueled by field and laboratory observations made during project Salt Vault in the 1960s (Bradshaw and Sanchez, 1969; Bradshaw and McClain, 1971).

Research at Sandia National Laboratories (SNL) associated with the Waste Isolation Pilot Plant (WIPP) from the late 1970s to the mid 1980s, developed experimental datasets to support the thermoporoelastic porous medium flow model for brine flow in salt (McTigue, 1986, 1990). This successful model discounted intragranular brine flow, to simplify mathematical and numerical models. In the 1980s, a few researchers included both intercrystalline porous media flow and intracrystalline brine inclusion movement, but they exclusively used vapor rather than liquid brine transport through the connected porosity (Olander et al., 1982). Ratigan (1984a) included brine inclusions and liquid flow through connected porosity, but did not include thermal expansion effects on the intergranular porosity.

Coupled THMC Processes

The general coupled nature of salt behavior has been known for over 60 years (Hess et al., 1957; Serata and Gloyne, 1959; Reynolds and Gloyne, 1960), but the details regarding the governing physical processes have only been fully understood and confirmed since large-scale brine migration tests results in the 1980s (Sherer, 1987). Figure 1.3 illustrates the relationships between Thermal, Hydraulic, Mechanical, and Chemical processes (THMC) for salt. Table 1.1 illustrates all combinations of the four coupled processes, including examples.

The governing equations for these four separate processes are coupled because each process potentially influences the others. Except under restrictive circumstances, we cannot solve for each result independently without significant error and loss of physical understanding. We present the coupled equations set, which must be solved to compute model-predicted THMC responses under proposed repository conditions in salt. These equations express mass, energy, and momentum

Figure 1.3. Cartoon representation of coupling in Thermal-Hydraulic-Mechanical-Chemical (THMC) systems (Su et al., 1995).

conservation. Conservation laws are then incorporated with phenomenological conservation laws, which are often based upon fitting linear relationships to laboratory testing results.

In Chapter 2 we give a general formulation for the coupled thermo-hydro-mechanical (THM) system based on a unifying flux formulation. In Chapter 3, we discuss the several mathematical and numerical solutions to the coupled brine flow problem. Numerical solution of coupled non-linear partial differential equations is a very large topic we do not reiterate here. We only mention some current models, and point to some historic models used to compute results given in the literature.

In Chapter 4, we recount what has been observed and learned through laboratory and in situ tests regarding the movement of brine in heated salt. Specifically we are interested in the release of natural brine from bedded or domal salt to a man-made borehole, as related to heat-generating radioactive waste disposal. We summarize both heated and isothermal brine inflow experiments. In the appendices we discuss relevant brine and gas permeability tests (Appendix C), and in situ and laboratory testing results related to disturbed rock zone development and characterization (Appendix B).

The brine inflow testing summary is comprehensive and useful for numerical modelers looking for datasets to benchmark numerical models against. The review is also a useful summary for laboratory and field experiment designers, illustrating what has already been done.

Processes	Example
$T = C$	phase change or solution heat
$T = H$	free convection, brine inclusion flow, and decrepitation
$T = M$	thermally induced microfractures and increased creep rate
$H = C$	density-dependent convective transport, salt dissolution, and pore opening/plugging
$H = M$	hydraulic fracturing or earth tide effects
$C - M$	waste package stress corrosion or dissolution creep
chemical reactions and density-dependent transport in heated flow systems
thermomechanical effects with mechanical property changes due to thermochemical reactions
thermoporoelasticity (McTigue, 1986)
poroelastic effects that influence chemical transport, including isothermal dissolution and precipitation
chemical reactions, dissolution, and transport in thermoporoelastic system

Table 1.1. THMC coupled processes combinations; single lines indicate weak coupling, double lines indicate strong coupling. Adapted from Tsang (1987).

Chapter 2

Theory of Brine Flow in Porous Media

In this chapter, we first present observations regarding brine migration mechanisms, which have historically motivated the development of the governing equations. The governing equations are presented in terms of conservation laws for each quantity being considered (i.e., energy, momentum, and mass). We then present the constitutive models, which produce the governing differential equations in terms of potentials, after combination with appropriate conservation laws. We present the non-dimensional governing equation forms, which allow us to assess the relative importance of the sometimes competing physical processes in coupled THM modeling. Lastly, we present some non-linear extensions to the main theory, including multi-phase flow and salt creep.

Brine Migration Mechanisms

Brine movement mechanisms vary by the different water types found in geologic salt (Figure 1.1). Figure 2.1 indicates the main brine migration mechanisms, and their relationships which are outlined in further detail below.

Figure 2.1. Relation between brine types and flow mechanisms.
Adapted from Shefelbine (1982).

Intergranular brine

Brine within intergranular porosity moves along interconnected macroscopic pores & grain-boundaries due to a combination of fluid pressure, thermal, and rock stress gradients (i.e., thermoporoelasticity – (McTigue, 1986, 1990)). The intergranular pore space is characterized at the macroscopic scale by its porosity and permeability. Permeability can vary by orders of magnitude due to changes in confining stress and damage. Salt damage includes microscopic fracturing (volume dilation) due to presence of deviatoric (i.e., shear) stresses near the excavation, which enhances rock permeability and porosity (see details and examples in Appendix B). Macroscopic fractures are often sub-parallel to excavation faces and are commonly failure points in the rock. Air-filled macroscopic fractures effectively act as barriers to brine flow.

Intergranular porosity most generally involves two-component flow of brine and air where dilation has increased salt porosity near the excavation. After porosity increases and air-entry pressure decreases near the excavation, a saturation front moves into the rock, sub-parallel to the excavation surface (Schlich and Jockwer, 1985; Beauheim et al., 1994; Stormont, 1997b). Most generally, brine flow in salt is treated as a variably saturated flow problem. We may approximate the system by bounding the saturated system by a moving material boundary representing the saturation front. This simplification has been used successfully in the groundwater hydrology literature (Neuman, 1972).

Brine in non-salt layers

Non-salt layers are often higher permeability than salt, and do not heal or creep like salt. Brine flow through these layers is governed by the same equations as intergranular brine flow in salt, but material properties may be significantly different.

Intragranular brine

Intragranular brine inclusions are a significant portion of total brine content in bedded salt (see Appendix A), but are not immediately available for flow under a stress or pressure gradient – they are located within salt crystals. Inclusions with low gas content will migrate across individual salt grains up a thermal gradient, towards a heat source (Bradshaw and Sanchez, 1969; Anthony and Cline, 1971). When brine inclusions reach the intergranular porosity between crystals, they tend to stay there, without migrating into the adjacent crystal (Olander, 1982). When inclusions have > 10% gas content (i.e., biphasic) they will often migrate faster than brine-only inclusions, but they will move down a thermal gradient, away from the heat source (Wilcox, 1968, 1969; Anthony and Cline, 1972). As evidenced by geologic brine inclusion stability under geothermal gradients, brine inclusion movement is apparently subject to threshold temperature gradients (Gnirk et al., 1981; Krause and Brodsky, 1987).

Brine inclusion decrepitation is failure due to the stress generated by the included phase's vapor

pressure, and the differential thermal expansion of salt crystal and brine inclusion (Wilcox, 1968). Upon decrepitation, intragranular brine escapes the local crystal structure, becoming intergranular brine (Figure 2.1). Decrepitation temperature can vary by confining pressure and inclusions size. Inclusions have been shown to grow in size and gas content upon heating to temperatures below decrepitation (Wilcox, 1968; Roedder and Bassett, 1981).

Water of hydration

Waters of hydration in non-salt hydrous minerals (e.g., polyhalite, carnallite, kainite, clay minerals, gypsum, kieserite, zeolites, and bischofite) often constitute the largest fraction of the total water content in impure geologic evaporite deposits, up to several tens of percent by weight (See Appendix A). Mineral-bound water is driven off by heating, releasing pure water vapor to the intergranular porosity (Figure 2.1). Water derived from this mechanism may further dissolve evaporites to reach chemical equilibrium in the intergranular pores. Clays, shale, gypsum, and zeolites release waters of hydration at relatively low temperatures ($\approx 100^\circ \text{C}$). Polyhalite and kieserite release water at temperatures above those expected under repository conditions ($\geq 340^\circ \text{C}$).

Conservation Laws

We primarily consider single-component brine flow in this report, but we address the additional complications due to “unsaturated” flow (multi-component immiscible flow of brine and gas/vapor). The fundamental conservation laws regarding mass, momentum, and energy for an arbitrary representative elementary volume are given in this section. The chapter ends with a variable list with definitions and metric units (Table 2.1) and a list of significant dimensionless quantities (Table 2.2).

Mass conservation

The mass continuity equation simply states the fluid mass rate of change in a bulk porous medium differential “control” volume equals the net fluid flow rate into the differential control volume, accounting for fluid sources or sinks within the control volume. The fluid mass balance can be written mathematically as (Bear and Corapcioglu, 1981; McTigue, 1986)

$$\frac{\partial}{\partial t}(\phi \rho_f) = -\nabla \cdot (\phi \rho_f \mathbf{v}_f) + F(\mathbf{x}, t), \quad (2.1)$$

where $\phi \rho_f$ is the fluid mass per unit bulk porous medium volume, ϕ is porosity, ρ_f is fluid density, $\mathbf{v}_f$ is the average fluid linear velocity vector, and $F(\mathbf{x}, t)$ [$\text{g} \cdot \text{m}^{-3} \cdot \text{s}^{-1}$] represents temporally and spatially variable fluid sinks and sources. Equation (2.1) may be rewritten in terms of the familiar

Darcy flux vector $\mathbf{q}_f$ as

$$\rho_f \frac{d_s \phi}{dt} + \phi \frac{d\rho_f}{dt} + \phi \rho_f \nabla \cdot \mathbf{v}_s = -\rho_f \nabla \cdot \mathbf{q}_f + F(\mathbf{x}, t), \quad (2.2)$$

where $\mathbf{q}_f = \phi(\mathbf{v}_f - \mathbf{v}_s)$, $\mathbf{v}_s$ is the solid velocity vector, and the total derivative operators are defined as $\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{v}_f \cdot \nabla$ and $\frac{d_s}{dt} = \frac{\partial}{\partial t} + \mathbf{v}_s \cdot \nabla$.

Similarly, the solid mass balance is given by

$$\frac{\partial}{\partial t}[(1 - \phi)\rho_s] = -\nabla \cdot [(1 - \phi)\rho_s \mathbf{v}_s], \quad (2.3)$$

where ρ_s is the solid matrix density. Equation (2.3) can be rewritten as

$$\frac{1}{1 - \phi} \frac{d_s \phi}{dt} - \frac{1}{\rho_s} \frac{d_s \rho_s}{dt} = \nabla \cdot \mathbf{v}_s. \quad (2.4)$$

The terms on left-hand side of equation (2.4) describe the changes in porosity and solid density due to solid deformation. The deformation may be due to stress and/or thermal effects. Substituting equation (2.4) into (2.2) and dividing throughout by ρ_f yields

$$\frac{\phi}{\rho_f} \frac{d\rho_f}{dt} - \frac{\phi}{\rho_s} \frac{d_s \rho_s}{dt} + \frac{1}{1 - \phi} \frac{d_s \phi}{dt} = -\nabla \cdot \mathbf{q}_f + f(\mathbf{x}, t). \quad (2.5)$$

where $f(\mathbf{x}, t) = F(\mathbf{x}, t)/\rho_f$. The first term on the left is the fluid mass rate of change due fluid density changes, and the other two terms are associated with fluid mass change due to changes in solid matrix density and porosity. Since elasticity assumptions have not been made, equations (2.4) and (2.5) are general. Linear elasticity assumptions are generally valid for small deformations, in which case the solid mass balance equation (2.4) reduces to (McTigue, 1986)

$$\nabla \cdot \mathbf{v}_s = \frac{d_s \epsilon_{kk}}{dt}, \quad (2.6)$$

where $\epsilon_{kk} = \text{trace}(\boldsymbol{\epsilon})$, and $\boldsymbol{\epsilon}$ is the solid strain tensor. Equation (2.6) simply states the solid dilatation rate reduces identically to the volumetric strain rate for small deformations. Hence, from equations (2.4) and (2.6) the fluid mass balance equation (2.2) becomes

$$\frac{\phi}{\rho_f} \frac{d\rho_f}{dt} + \frac{1 - \phi}{\rho_s} \frac{d_s \rho_s}{dt} + \frac{d_s \epsilon_{kk}}{dt} = -\nabla \cdot \mathbf{q}_f + f(\mathbf{x}, t). \quad (2.7)$$

The first and second terms on the left are the pore fluid and solid matrix density changes due to thermal and mechanical (stress) loading. The third term is the corresponding bulk rock dilatation rate.

Biot (1941) derived the original poroelasticity relations assuming an incompressible fluid, in which case the first term in equation (2.7) vanishes identically. Bear and Corapcioglu (1981) and McTigue (1986) assumed constant solid density, in which case the second term in equation (2.7) vanishes. McTigue (1986) further ignored all convective terms, linearizing the fluid density as

$$\phi \rho_f = \phi_0 \rho_{f0} (1 - \epsilon_f), \quad (2.8)$$

where ϕ_0 and ρ_{f0} are reference porosity and reference fluid density and ε_f is fluid dilatation (volumetric strain). McTigue (1986) further neglected the nonlinear terms involving products of fluid dilatation and velocities, leading to

$$\frac{\partial \zeta}{\partial t} = -\nabla \cdot \mathbf{q}_f + f(\mathbf{x}, t). \quad (2.9)$$

where $\zeta = \phi_0 (\varepsilon_{kk} - \varepsilon_f)$ is the increment of fluid content (e.g., Wang (2000)).

Momentum conservation

Neglecting body and inertial forces, Newton's second law can be shown to reduce to

$$\nabla \cdot \boldsymbol{\tau} = \mathbf{0}, \quad (2.10)$$

where $\boldsymbol{\tau}$ is the total stress tensor.

Energy conservation

Energy conservation indicates the energy change rate within a bulk porous medium differential control volume equals the net rate of energy flow into the control volume, accounting for sources or sinks. Based on Bear and Corapcioglu (1981), fluid energy conservation is

$$\frac{d}{dt}(\phi \rho_f c_{v,f} \theta) = -\nabla \cdot \mathbf{q}_{h,f} + H(\mathbf{x}, t), \quad (2.11)$$

where $\mathbf{q}_{h,f}$ is the conduction heat flux in the fluid, $c_{v,f}$ is the constant-volume fluid heat capacity, θ is temperature, and $H(\mathbf{x}, t)$ [$\text{W} \cdot \text{m}^{-3}$] represents temporally and spatially variable energy sources. For slow-moving fluids, the solid is assumed to be in thermal equilibrium with the fluid, therefore energy conservation for the solid is

$$\frac{d}{dt}[(1 - \phi) \rho_s c_{v,s} \theta] = -\nabla \cdot \mathbf{q}_{h,s}, \quad (2.12)$$

where $\mathbf{q}_{h,s}$ is the conduction heat flux in the solid and $c_{v,s}$ is the solid heat capacity. Summing equations (2.11) and (2.12) the energy conservation equation for the bulk porous medium becomes

$$\rho c_v \frac{d_s \theta}{dt} + \rho_f c_{v,f} \mathbf{q}_f \cdot \nabla \theta + \theta \left\{ c_{v,f} \frac{d}{dt}(\phi \rho_f) + c_{v,s} \frac{d_s}{dt}[(1 - \phi) \rho_s] \right\} = -\nabla \cdot \mathbf{q}_h + H(\mathbf{x}, t), \quad (2.13)$$

where $\mathbf{q}_h = \mathbf{q}_{h,f} + \mathbf{q}_{h,s}$, $\rho c_v = \phi \rho_f c_{v,f} + (1 - \phi) \rho_s c_{v,s}$, and c_v is a bulk heat capacity. The first term on left-hand side of equation (2.13) is the thermal energy rate of change in a porous medium differential volume, including the convection term for solid medium flow. The second term represents convective heat transfer term due fluid flow relative to the solid matrix, while the third term in brackets represents sources due to adiabatic solid and fluid deformation. The right-hand-side gives

the bulk medium heat flux divergence and heat source or sink. Expanding the term in brackets in equation (2.13) and rearranging, one obtains

$$\rho c_v \frac{d_s \theta}{dt} + \rho_f c_{v,f} [\mathbf{q}_f \cdot \nabla \theta - \theta \nabla \cdot \mathbf{q}_f + \theta (\mathbf{v}_f - \mathbf{v}_s) \cdot \nabla \phi] = -\nabla \cdot \mathbf{q}_h + \rho c_v \theta \frac{d_s \epsilon_b}{dt} + H(\mathbf{x}, t). \quad (2.14)$$

Setting $\phi \approx \phi_0$ and neglecting convective terms due to solid displacement in $\mathbf{v}_s$ leaves

$$\rho c_v \frac{\partial \theta}{\partial t} + \rho_f c_{v,f} [\mathbf{q}_f \cdot \nabla \theta - \theta \nabla \cdot \mathbf{q}_f] = -\nabla \cdot \mathbf{q}_h + \rho c_v \theta \frac{\partial \epsilon_b}{\partial t} + H(\mathbf{x}, t). \quad (2.15)$$

Constitutive Equations

In this section, we present the constitutive models which are used to express fluxes across the surfaces of the control volume in terms of potentials, which become the dependent variables in the governing differential equations.

Fluid flux

We consider the total fluid flux, $\mathbf{q}_f$, which has contributions from fluid pressure and thermal gradients

$$\mathbf{q}_f = \mathbf{q}_{f,p} + \mathbf{q}_{f,\theta}. \quad (2.16)$$

Most generally, additional terms due to osmotic fluxes and electric currents could also be included (de Groot and Mazur, 1984; Haase, 1990). The contribution due to pressure gradients is given by Darcy's law, viz.,

$$\mathbf{q}_{f,p} = -\frac{\mathbf{k}}{\mu} \nabla (p + \rho_f g z) \quad (2.17)$$

where $\mathbf{k}$ is the permeability tensor, μ is dynamic viscosity, p is fluid pore pressure, g is acceleration due to gravity, and z is vertical position (elevation head). Intercrystalline brine flow due to thermal gradients is the Soret effect, given by

$$\mathbf{q}_{f,\theta} = -\Lambda_t \nabla \theta \quad (2.18)$$

where Λ_t is the Soret or thermophoresis coefficient. The total fluid flux, due to the two components considered here, is

$$\mathbf{q}_f = -\frac{\mathbf{k}}{\mu} \nabla (p + \rho_f g z) - \Lambda_t \nabla \theta. \quad (2.19)$$

Any additional fluid fluxes due to other potential gradients, including those due to brine inclusions or chemical gradient, may be included here in equation (2.19) as additive terms. Brine inclusion can either be treated as contribution to the source term in the governing fluid flow equation, or as a fluid flux driven by thermal gradients.

Thermal flux

The total heat flux $\mathbf{q}_h$ has contributions from both thermal and pressure gradients,

$$\mathbf{q}_h = \mathbf{q}_{h,\theta} + \mathbf{q}_{h,p}, \quad (2.20)$$

and most generally will include a thermal filtration flux and a flux due to electrical current (de Groot and Mazur, 1984; Haase, 1990). The thermal conductive head flux through a bulk saturated porous medium is given by Fourier's law, viz.,

$$\mathbf{q}_{h,\theta} = -\kappa \nabla \theta \quad (2.21)$$

where $\kappa = \phi \kappa_f + (1 - \phi) \kappa_s$ is the bulk thermal conductivity in terms of fluid and solid thermal conductivities. When a pressure gradient is maintained across an originally isothermal saturated porous medium, the flow (or mass diffusion) of fluid leads to a temperature gradient, the Dufour effect (not the same as convective heat transfer). Heat flux resulting from pressure gradients is given by

$$\mathbf{q}_{h,p} = \Lambda_h \nabla p \quad (2.22)$$

where Λ_h is the Dufour coupling coefficient. The total heat flux, due to the two components considered here, is

$$\mathbf{q}_h = -\kappa \nabla \theta + \Lambda_h \nabla p. \quad (2.23)$$

Additional flux cross-effects could also be included here additively.

Thermoporoelasticity relations

We assume coupled thermoelastic and poroelastic deformation of the solid matrix. The strain tensor is related to the stress tensor, pore pressure, and temperature by

$$\boldsymbol{\varepsilon} = \frac{1}{2G} \left[\boldsymbol{\tau} - \frac{\nu}{1+\nu} \text{trace}(\boldsymbol{\tau}) \mathbf{I} \right] + \frac{\eta_0}{3K} p \mathbf{I} + \frac{\beta_s}{3} (\theta - \theta_0) \mathbf{I} \quad (2.24)$$

where ν is the drained Poisson's ratio, G is the bulk shear modulus, K is the macroscopic bulk modulus, and $\eta_0 = 1 - K/K_m$ is the Biot-Willis coefficient which satisfies $\eta_0 \in [\phi, 1]$, $K_m = \rho_s \frac{\partial \sigma_{kk}}{\partial \rho_s} \Big|_{p=\text{const}}$ is the macroscopic rock matrix material bulk modulus, and $\mathbf{I}$ is the identity tensor.

Thus, given $K = \frac{2}{3}G(1 + \nu)/(1 - 2\nu)$, it follows

$$\varepsilon_{kk} = \text{trace}(\boldsymbol{\varepsilon}) = \frac{1}{K} (\sigma_{kk} + \eta_0 p) + \beta_s (\theta - \theta_0), \quad (2.25)$$

where $\sigma_{kk} = \frac{1}{3} \text{trace}(\boldsymbol{\tau})$ is the mean normal stress.

The definition of ε_{kk} (2.25) does not account for changes in fluid density associated with pressure and thermal effects. To account for these effects we set $\rho_f = \rho_f(p, \theta)$ and it follows (Bear and Corapcioglu, 1981)

$$\frac{d\rho_f}{dt} = \frac{\rho_f}{K_f} \frac{dp}{dt} - \rho_f \beta_f \frac{d\theta}{dt}, \quad (2.26)$$

where $K_f = \rho_f \frac{\partial p}{\partial \rho_f} \Big|_{\theta=\text{const}}$ is the coefficient of fluid bulk modulus (reciprocal of fluid compressibility) at constant temperature, and $\beta_f = - \frac{1}{\rho_f} \frac{\partial \rho_f}{\partial \theta} \Big|_{p=\text{const}}$ is the fluid volumetric thermal expansion coefficient at constant pressure. Additionally, to account for thermal effects on solid density we set $\rho_s = \rho_s(\sigma_{kk}, \theta)$, which leads to

$$\frac{d_s \rho_s}{dt} = \frac{\rho_s}{K_s} \frac{d_s \sigma_{kk}}{dt} - \rho_s \beta_s \frac{d_s \theta}{dt}, \quad (2.27)$$

where $K_s = \left(\frac{1}{\rho_s} \frac{\partial \rho_s}{\partial \sigma_{kk}} \right)^{-1} \Big|_{\theta=\text{const}}$ is the rock matrix macroscopic bulk modulus at constant temperature and $\beta_s = - \frac{1}{\rho_s} \frac{\partial \rho_s}{\partial \theta} \Big|_{\sigma=\text{const}}$ is the solid volumetric thermal expansion coefficient at constant confining pressure.

Thermoporoelasticity Governing Equations

The governing equations of thermoporoelasticity are obtained by combining the conservation laws and the constitutive equations given in the previous sections. To obtain the fluid flow equation substitute equations (2.25), (2.26), and (2.27) into equation (2.7). Upon rearranging terms one obtains

$$\frac{\phi}{K_f} \frac{dp}{dt} + \frac{1-\phi}{K_s} \frac{d_s \sigma_{kk}}{dt} + \frac{1}{K} \frac{d_s}{dt} [\sigma_{kk} + \eta_0 p - \phi(\beta_f - \beta_s) K \theta] = -\nabla \cdot \mathbf{q}_f + \beta_f \mathbf{q}_f \cdot \nabla \theta + f(\mathbf{x}, t). \quad (2.28)$$

The three terms on the left of equation (2.28) can be linearized by replacing ϕ with a reference porosity ϕ_0 and by neglecting the convective terms. Upon rearranging terms and incorporating equation (2.19) for the first term on right-hand side leads to (Rice and Cleary, 1976; McTigue, 1986)

$$\frac{\eta_1}{3\eta_2} \frac{\partial}{\partial t} \left(\sigma_{kk} + \frac{3}{B} p \right) - \phi_0(\beta_f - \beta_s) \frac{\partial \theta}{\partial t} = \frac{\mathbf{k}}{\mu} \nabla^2 p + \Lambda_t \nabla^2 \theta + \beta_f \mathbf{q}_f \cdot \nabla \theta + f(\mathbf{x}, t), \quad (2.29)$$

where $\eta_1 = \frac{6(v_u - v)}{B(1-v)(1+v_u)}$, $\eta_2 = \frac{4G(1+v)}{3(1-v)}$, v_u is the undrained Poisson's ratio, and B is Skempton's coefficient. The terms on the left-hand side of (2.29) are the change in fluid mass per unit bulk porous medium volume due to a change in pore fluid pressure, mechanical loading (stress state), and thermal loading. The first term on the right-hand side is the Darcy flux divergence, and the last term is flux divergence due to rock dilatation.

As shown by Rice and Cleary (1976) for poroelasticity and extended by McTigue (1986) to thermoporoelasticity, upon invoking equation (2.24) and the well-known St. Venant compatibility equation, the momentum balance (2.10) is

$$\nabla^2 (\sigma_{kk} + \eta_1 p + \eta_2 \beta_s \theta) = 0. \quad (2.30)$$

This is the governing equation for the mean normal stress. Without loss of generality, equation (2.30) may be combined with equation (2.29) to yield a governing equation for $\sigma_{kk} + 3p/B$.

The governing equation for heat flow is obtained by substituting equation (2.23) for the thermal heat flux into the energy balance equation (2.15), yielding

$$\begin{aligned} \rho c_v(1 - \beta_s \theta) \frac{\partial \theta}{\partial t} = & \kappa \nabla^2 \theta - \Lambda_h \nabla^2 p + \rho_f c_{v,f} (\theta \nabla \cdot \mathbf{q}_f - \mathbf{q}_f \cdot \nabla \theta) \\ & + \frac{\rho c_v \theta}{K} \frac{\partial}{\partial t} (\sigma_{kk} + \eta_0 p) + H(\mathbf{x}, t). \end{aligned} \quad (2.31)$$

For negligible thermal effects due to solid and fluid expansion, no sources or sinks, and negligible heat convection due fluid flow, equation (2.31) reduces to

$$\rho c_v \frac{\partial \theta}{\partial t} = \kappa \nabla^2 \theta. \quad (2.32)$$

This is the well-known heat conduction equation and is the basis of the analytical solutions of thermoelastic theory of McTigue (1986).

Nondimensionalization of governing equations

Equations (2.29), (2.30), and (2.31) constitute the governing equations for the thermoporoelastic problem and can be solved for the three unknowns p , σ_{kk} , and θ . These equations are nonlinear partial differential equations due to thermoporoelastic coupling and convective heat transport by fluid flow relative to the solid matrix. We express the governing equations in dimensionless form to reduce the number of free parameters in the governing equations (e.g., Lin and Segel (1988, Chap. 6)). We identify critical dimensionless groups and time scales associated with the various brine flow mechanisms in deforming media under thermal forcing.

Equation (2.29) can be rewritten in dimensionless form by choosing $t_D = t/T_c$, $\mathbf{x}_D = \mathbf{x}/L_c$, $p_D = p/P_c$, $\sigma_{kk,D} = \sigma_{kk}/\Sigma_c$, and $\theta_D = \theta/\Theta_c$. Since we are focused on flow toward a heated borehole we set $\Theta_c = q_{h,0}R_b/\kappa$ as a characteristic temperature and $L_c = R_b$ as a characteristic length, where $q_{h,0}$ is the constant heat flux delivered to a borehole and R_b is the borehole radius. From this, it is convenient to use $P_c = \beta_D/S_p$ as the characteristic pressure and $T_c = R_b^2/\alpha_f$ as the characteristic time, where $\beta_D = \phi_0(\beta_{D,f} - \beta_{D,s})$, $\beta_{D,f} = \beta_f\Theta_c$, $\beta_{D,s} = \beta_s\Theta_c$, $\alpha_f = k_1/(\mu S_p)$, k_1 is permeability in the largest principle direction, $\alpha_h = \kappa/(\rho c_v)$, and

$$S_p = \frac{\eta_1}{\eta_2 B} = \frac{9(v_u - v)}{2B^2 G(1 + v)(1 + v_u)}.$$

When we substitute these quantities into (2.29) we obtain the dimensionless expression

$$\frac{\partial}{\partial t_D} (S\sigma_{kk,D} + p_D) - \frac{\partial \theta_D}{\partial t_D} = \mathbf{k}_D \nabla_D^2 p_D + \Lambda_{t,D} \nabla_D^2 \theta_D + \beta_{D,f} \mathbf{q}_{f,D} \cdot \nabla_D \theta_D + f_D(\mathbf{x}_D, t_D), \quad (2.33)$$

where $\mathbf{k}_D = \mathbf{k}/k_1$ is the permeability anisotropy tensor, $\alpha_D = \alpha_h/\alpha_f$, $S = \Sigma_c \eta_1/(3\eta_2\beta_D)$, $q_{f,0} = \beta_D \alpha_f/R_b$, $\Lambda_{t,D} = \Theta_c \Lambda_t/(q_{f,0} R_b)$, ∇_D is the dimensionless gradient operator, and

$$\mathbf{q}_{f,D} = -\mathbf{k}_D \nabla_D (p_D + \hat{z}_D) - \Lambda_{t,D} \nabla_D \theta_D, \quad (2.34)$$

with $\hat{z}_D = \rho_f g z/P_c$. Following equations (2.33) and (2.34), under the assumptions of thermo-poroelasticity, we present an important dimensionless quantity for evaluating the significance of intergranular brine migration under thermal gradients relative to pressure gradients

$$\Lambda_{t,D} = \frac{\Theta_c \Lambda_t}{q_{f,0} R_b} = \frac{\Lambda_t}{\phi_0 (\beta_f - \beta_s) \alpha_f}. \quad (2.35)$$

The parameters in this dimensionless number can be determined from laboratory experiments.

Upon nondimensionalization, the equation for the mean normal stress (2.30) becomes

$$\nabla_D^2 (\sigma_{kk,D} + p_D + Z \theta_D) = 0, \quad (2.36)$$

where we have chosen the characteristic mean stress $\Sigma_c = \eta_1 P_c$ and defined the dimensionless parameter

$$Z = \frac{\eta_2 S_p}{\eta_1 \phi_0 (\beta_f/\beta_s - 1)} = \frac{2BGS_p(1+\nu)(1+\nu_u)}{9\phi_0(\beta_f/\beta_s - 1)(\nu_u - \nu)}. \quad (2.37)$$

The dimensionless parameter Z can be used to determine the importance of thermal loading on the stress field and is estimable from measurements obtainable in laboratory experiments. Values where $Z \rightarrow 0$ imply thermal loading effects are negligible.

Defining a new characteristic time with respect to the thermal diffusivity, $\tilde{T}_c = R_b^2/\alpha_h$, the dimensionless form of (2.31) becomes

$$\begin{aligned} (1 - \beta_{D,s} \theta_D) \frac{\partial \theta_D}{\partial t_D^*} &= \nabla_D^2 \theta_D + \text{Pe} (\theta_D \nabla_D \cdot \mathbf{q}_{f,D} - \mathbf{q}_{f,D} \cdot \nabla_D \theta_D) \\ &+ \frac{\theta_D}{K_D} \frac{\partial}{\partial t_D^*} (\sigma_{kk,D} + \eta_D p_D) - \Lambda_{h,D} \nabla_D^2 p_D + H_D(\mathbf{x}_D, t_D), \end{aligned} \quad (2.38)$$

where $t_D^* = t/\tilde{T}_c$, $\text{Pe} = \beta_D/\alpha_{D,f}$ is the Péclet number, $\Lambda_{h,D} = \Lambda_h \phi_0 (\beta_f - \beta_s)/(\kappa S_p)$, $\alpha_{D,f} = \alpha_{h,f}/\alpha_f$, $\alpha_{h,f} = \kappa/(\rho_f c_{v,f})$, $K_D = K/\Sigma_c$, and $\eta_D = \eta_0/\eta_1$. The Péclet number quantifies the relative importance of conductive and convective heat transfer. Small Pe values signify conduction-dominated heat transfer, while large values indicate convection is dominant. This can be used to design experiments so convective heat transfer is negligible. The dimensionless number $\Lambda_{h,D}$ can be used to determine the relative importance of intergranular Dufour effects; for $\Lambda_{h,D} \rightarrow 0$, these effects can be neglected. Values of $\beta_{D,s} \rightarrow 0$ imply the effects of thermal expansion on heat transfer can be neglected, and for values of $K_D \rightarrow \infty$, thermal effects due to stress and fluid pore pressure loading can be neglected. The ratio of the two characteristic times is $T_c/\tilde{T}_c = \alpha_D$. The relative time scales over which fluid flow and heat transfer occur are determined by α_D , the ratio of the thermal and hydraulic diffusivities.

Brine Inclusion Contribution to Total Brine Migration

There are two possible ways to incorporate the contribution of intragranular brine inclusions to the total fluid mass migrating through bedded salt under the action of thermal gradients:

1. Treating the flow domain as a single continuum in which the brine inclusion flux term appears as an additive term to the total fluid flux due to thermal gradients. In this case equation (2.18) becomes

$$\mathbf{q}_{f,\theta} = -\Lambda_t \nabla \theta + \mathbf{q}_{f,\text{inc}}, \quad (2.39)$$

where $\mathbf{q}_{f,\text{inc}}$ is the fluid flux due to movement of brine inclusions under a thermal gradient.

2. Treating the flow domain as two separate continua, the intracrystalline and intercrystalline domains are coupled at the interface between the salt crystals and intercrystalline porosity. The salt crystals with brine inclusions act as sources supplying brine to the intercrystalline porosity network.

The first case assumes an unimpeded path through the salt crystal matrix (no “loose” salt grain boundaries or non-salt inclusions). In this case, if n is the total brine inclusion volume per unit bulk volume of rock salt and the inclusions have $< 10\%$ gas content (Wilcox, 1969), then the flux due to inclusion migration and intercrystalline flow due to thermal gradients is given by

$$\mathbf{q}_{f,\text{inc}} = n\mathbf{v}(\mathbf{x}, t) - \Lambda \nabla \theta, \quad (2.40)$$

where $\mathbf{v}$ is the linear velocity of a single brine inclusion in a halite crystal, and Λ is the Dufour coefficient for intracrystalline fluid flow due to thermal gradients (different from the intercrystalline Λ_t in equation (2.18)). The linear velocity of a single brine inclusion in a halite crystal is (Anthony and Cline, 1971)

$$\mathbf{v}(\mathbf{x}, t) = \Lambda_{\text{inc}} \nabla \theta - \mathbf{v}_{\text{irr}}(\mathbf{x}, t), \quad (2.41)$$

where

$$\Lambda_{\text{inc}} = fD \frac{C_\ell}{C_s} \left(\frac{1}{C_E} \frac{\partial C_E}{\partial \theta} + \chi \right),$$

C_ℓ is the salt concentration in brine, C_s is the molar salt concentration in the solid, C_E is the equilibrium salt solubility in brine, D is the salt diffusion coefficient in brine, χ is the intracrystalline Soret coefficient (different from the intercrystalline Λ_h in equation (2.22)), R is the universal gas constant, f is the proportionality constant between brine and solid thermal gradients ($\nabla \theta_\ell = f \nabla \theta$), and $\mathbf{v}_{\text{irr}}$ accounts for the effects of irreversible processes associated with the changes in chemical potential at the solid-liquid interface during deposition and dissolution of salt as the droplet migrates through the salt crystal.

In most natural salt, brine inclusion migration only continues to a grain boundary, where most inclusions loose their brine to the intercrystalline porosity (Roedder and Belkin, 1980). Under these conditions contribution of brine inclusion may be treated as a source function component

$f(\mathbf{x}, t)$ in the brine flow governing equation. Based on Jenks and Claiborne (1981), Olander et al. (1982) showed this source term is

$$f(\mathbf{x}, t) = \frac{3\phi_{\text{inc}}}{2d_g} H(2 - H) \mathbf{v}(\mathbf{x}, t) \quad (2.42)$$

where $\rho_f \phi_{\text{inc}}$ is the quantity of brine in the inclusions contained in a unit volume of salt, d_g is the effective brine inclusion diameter, and

$$H = 1 - \frac{1}{d_g} \int_0^t \mathbf{v}(\mathbf{x}, t') dt'. \quad (2.43)$$

Equation (2.42) can be rewritten as

$$f_D(\mathbf{x}_D, t_D) = U \mathbf{v}_D(\mathbf{x}_D, t_D) \quad (2.44)$$

where $U = \frac{3R_b \phi_{\text{inc}}}{2d_g \beta_D} H(2 - H)$. The dimensionless number U provides a measure of brine inclusion source term relative importance. As can be seen from (2.42) the source term makes solution of the flow problem incorporating a brine inclusion source term impractical without recourse to iterative numerical techniques.

At the decrepitation point, the brine vapor pressure exceeds the capability of the salt crystal to contain it, and the brine is released to the intergranular porosity. This could be represented as an additional source term $f(\mathbf{x}, t)$, which is activated when the salt temperature reaches a specified threshold temperature.

Inelastic Deformation Effects

The theory presented above shows brine flow in rock salt is strongly dependent on solid matrix deformation. However, the theory is limited to small elastic salt deformation. Laboratory and in situ experiments (Serata and Gloyna, 1959; Hansen and Mellegard, 1979; Pfeifle et al., 1983; Carter and Hansen, 1983) in salt have clearly shown salt undergoes transient inelastic deformation, where the strains continue to change with time under constant stress. This transient behavior is commonly referred to as creep, and under such conditions the stress-strain constitutive relation and the solid mass conservation statement given in equations (2.24) and (2.6) are no longer valid as they are associated with the instantaneous elastic component of total transient deformation. Typical salt creep behavior is depicted in Figure 2.2 where the three commonly observed phases of the transient strain curve are depicted schematically. It comprises the instantaneous elastic response and the transient inelastic response consisting of a nonlinear primary phase, a linear secondary (also referred to as steady-state creep) phase and a nonlinear tertiary phase which is rapidly followed by failure. The mechanisms responsible for creep are well elucidated in Spiers et al. (1988) and elsewhere. Several empirical models have been proposed for modeling creep, which typically decompose total creep strain as (Jaeger and Cook, 1979)

$$\epsilon = \epsilon^E + \epsilon_1(t) + \epsilon_2(t) + \epsilon_3(t) \quad (2.45)$$

Figure 2.2. Typical salt creep behavior showing the three major transient strain phases in response to constant stress. Adapted from Jaeger and Cook (1979).

where ε^E is the instantaneous elastic strain, $\varepsilon_1(t)$ is transient (primary) creep, $\varepsilon_2(t) = Vt$ is steady-state (secondary) creep, and $\varepsilon_3(t)$ describes accelerating (tertiary) creep. For transient creep, Serata and Gloyna (1959) proposed the empirical model

$$\varepsilon_1(t) = \varepsilon_{t,0} \ln(t) \quad (2.46)$$

for rock salt, where $\varepsilon_{t,0}$ is total transient creep strain. Based on thermodynamic considerations, Carter and Hansen (1983) proposed an empirical power-law relation for transient creep

$$\varepsilon_1(t) = k\theta^p \sigma^n t^m \quad (2.47)$$

where σ is differential axial stress, θ is absolute temperature, and k , p , n and m are empirical constants. This model has been used with different empirical constants to model salt creep (Boresi and Deere, 1963; Lomenick and Bradshaw, 1969; Thoms et al., 1973). Reviews of the various simple functional forms $\varepsilon_1(t)$ and $\varepsilon_2(t)$ can assume, are found in Jaeger and Cook (1979), Carter and Hansen (1983), and Jaeger et al. (2007).

Rheological laws provide general stress-strain constitutive relations to be used with equations (2.24) and (2.6) to describe transient rock behavior under various boundary conditions. The simplest of these is the Maxwell or elasto-viscous equation given by

$$\frac{d\varepsilon}{dt} = \frac{1}{k} \frac{d\sigma}{dt} + \frac{\sigma}{\eta}, \quad (2.48)$$

where k is a modulus [Pa] (analogous to spring stiffness) and η is a viscosity [Pa·s] (analogous to dashpot resistance).

For elastic solids the second term on right-hand side vanishes and the equation reduces to Hooke's law, while for Newtonian fluids the first term on right-hand side vanishes and the relation becomes Newton's viscosity law. Equation (2.48) only captures the elastic and steady-state creep components. Another model, which captures elastic deformation and primary creep is the generalized Kelvin model,

$$\eta_1 \frac{d\sigma}{dt} + (k_1 + k_2)\sigma = k_2 \left(\eta_1 \frac{d\varepsilon}{dt} + k_1 \varepsilon \right). \quad (2.49)$$

Combining the Maxwell (2.48) and generalized Kelvin (2.49) models yields a model for a Burgers substance that exhibits elastic strain, transient, and steady-state creep,

$$\frac{\eta_1}{k_2} \frac{d^2\sigma}{dt^2} + \left(1 + \frac{k_1}{k_2} + \frac{\eta_1}{\eta_2} \right) \frac{d\sigma}{dt} + \frac{k_1}{\eta_2} \sigma = \eta_1 \frac{d^2\varepsilon}{dt^2} + k_1 \frac{d\varepsilon}{dt}. \quad (2.50)$$

This equation can be solved for the case where a stress σ_0 is applied instantaneously at $t = 0$ giving the model (Webster et al., 1969)

$$\varepsilon(t) = \frac{\sigma_0}{k_2} + \frac{\sigma_0}{k_1} \left(1 - e^{-t/\tau} \right) + \frac{\sigma_0}{\eta_2} t, \quad (2.51)$$

where $\tau = \eta_1/k_1$ is a characteristic time. This equation was used by Herrmann and Lauson (1981) to model salt creep. The model may be extended to account for a transient stress $\sigma(\tau)$ by using linear superposition, yielding

$$\varepsilon(t) = \int_0^t \sigma(\tau) f(t - \tau) d\tau, \quad (2.52)$$

where $f(t)$ is the strain resulting from an instantaneous stress at $t = 0$. Equation (2.52) is a convolution integral describing viscoelastic materials with stress history memory, where $f(t)$ is the memory function.

More advanced models for creep are available in the literature, including the those of Carter and Heard (1970), Munson and Dawson (1979, 1981), Fossum et al. (1996), and Munson (1997). All these models and those described above may be used as constitutive relations for transient salt stress-strain behavior and incorporated into the solid-phase mass balance equation and the momentum conservation equations yielding quasi-linear and nonlinear governing equations to be solved numerically.

Multi-phase/Multi-component Systems

Brine flow toward a borehole or excavation in salt is fundamentally a multi-phase (multi-component) process even when there is no thermal forcing. The three phases being the solid (rock salt), liquid (brine), and air (which includes vapor) (Rodwell et al., 1999, §6.5). The two primary mechanisms leading to multi-phase flow conditions are thermal loading that can cause evaporation, and excavation damage that causes salt matrix dilatation. The process by which excavation leads to multi-phase conditions in rock salt are discussed by Stormont et al. (1987, 1991a)

and Stormont (1997a). The small-scale mine-by experiment conducted at WIPP found a saturation boundary formed rapidly between the wall of a large borehole and the edge of the disturbed rock zone (Figure C.3).

McTigue (1985, Appendix A) used the continuum theory of mixtures to derive general mass, momentum, and energy conservation equations of multi-phase flow, which he simplified to a solid-liquid (air/vapor phase neglected) mixture without dissolution. The governing equations were obtained from the linear thermoporoelasticity constitutive equations. Olivella et al. (1994) developed a more general formulation of the theory for multi-phase brine flow in salt, allowing for inelastic deformation (creep), dissolution and precipitation of salt, brine evaporation, air dissolution in brine, and brine transport by inclusion migration.

Mass, momentum, and energy conservation

The formulation presented below follows Olivella et al. (1994). The total mass balance for salt is given by

$$\frac{\partial}{\partial t} [\omega_s^h (1 - \phi) \rho_s + \omega_l^h \hat{\omega}_l \phi \rho_l] = -\nabla \cdot (\mathbf{j}_s^h + \mathbf{j}_l^h) + f_h \quad (2.53)$$

where $\hat{\omega}_l$ is the liquid volume per unit pore space volume (moisture saturation), ω_s^h and ω_l^h are the salt mass fractions in the solid and liquid phases, respectively, $\mathbf{j}_s^h$ and $\mathbf{j}_l^h$ are the salt mass fluxes in the solid and liquid phases, respectively, and f_h is the salt source/sink function. Salt flux in the liquid phase is simply advection and dispersion of dissolved salt in brine (water). The total mass balance for water is given by

$$\frac{\partial}{\partial t} [\omega_s^w (1 - \phi) \rho_s + \omega_l^w \hat{\omega}_l \phi \rho_l + \omega_g^w \hat{\omega}_g \phi \rho_g] = -\nabla \cdot (\mathbf{j}_s^w + \mathbf{j}_l^w + \mathbf{j}_g^w) + f_w, \quad (2.54)$$

where $\hat{\omega}_g$ is gas volume per unit pore space volume (gas saturation), ω_s^w , ω_l^w , and ω_g^w are the water mass fractions in the solid, liquid, and gas phases, respectively, $\mathbf{j}_s^w$, $\mathbf{j}_l^w$, and $\mathbf{j}_g^w$ are water mass fluxes in solid, liquid, and gas phases, respectively, and f_w is the water source/sink function. Similarly, the total air mass balance has the form

$$\frac{\partial}{\partial t} [(\omega_l^a \hat{\omega}_l \rho_l + \omega_g^a \hat{\omega}_g \rho_g) \phi] = -\nabla \cdot (\mathbf{j}_l^a + \mathbf{j}_g^a) + f_a, \quad (2.55)$$

where ω_l^a and ω_g^a are air mass fractions in the liquid and gas phases, respectively, $\mathbf{j}_l^a$ and $\mathbf{j}_g^a$ are air mass fluxes in the liquid and gas phases, respectively, and f_a is the air source/sink function.

Momentum conservation is still given by equation (2.10). Olivella et al. (1994) however, allow for a constitutive stress-strain relation accounting for inelastic time-dependent deformation (creep).

The multi-phase energy conservation equation is (Olivella et al., 1994)

$$\frac{\partial}{\partial t} [(1 - \phi) \rho_s E_s + \hat{\omega}_l \phi \rho_l E_l + \hat{\omega}_g \phi \rho_g E_g] = -\nabla \cdot (\mathbf{j}_c + \mathbf{j}_{Es} + \mathbf{j}_{El} + \mathbf{j}_{Eg}) + f_E, \quad (2.56)$$

where E_s , E_l , and E_g are specific internal energies of the solid, liquid and gas phases, $\mathbf{j}_c$ is conductive heat flux, $\mathbf{j}_{Es}$, $\mathbf{j}_{El}$, and $\mathbf{j}_{Eg}$ are heat fluxes associated with solid, liquid and gas motion, and f_E is the energy source/sink function.

In addition to these equations, we need the compatibility conditions

$$\hat{\omega}_l + \hat{\omega}_g = 1, \quad (2.57)$$

$$\omega_s^h + \omega_s^w = 1, \quad (2.58)$$

$$\omega_l^h + \omega_l^w + \omega_l^a = 1, \quad (2.59)$$

and

$$\omega_g^w + \omega_g^a = 1. \quad (2.60)$$

The multi-phase problem is completed with the constitutive relations discussed in the following section.

Constitutive relations

Darcy's law (2.17) relates fluid fluxes to fluid pressure, while Fourier's law (2.21) relates conductive energy fluxes to thermal gradients. For Darcy's law, Olivella et al. (1994) treat intrinsic permeability as a function of solid deformation, since this affects medium porosity and its connectivity. Fick's law (Bird et al., 1960) is used to relate dissolved species dispersion fluxes to concentration gradients. Hassanizadeh (1986) generalized Darcy's and Fick's laws to allow for effects of pressure and concentration gradients, as well as density and thermal gradients on fluid fluxes and species dispersion. Relations are needed to describe salt and air (Henry's law) dissolution and the equation of state expressing the gas density variation with capillary pressure and temperature. These are discussed in Olivella et al. (1994).

When two immiscible fluids are in contact, such as water (or brine) and air (gas), a pressure discontinuity exists across the interface separating the fluids. The pressure differential across that interface is the capillary pressure, p_c . For an air-water interface, it is defined as

$$p_c(\hat{\omega}_l) = p_g - p_l, \quad (2.61)$$

where p_g is air pressure and p_l is water pressure. The capillary pressure is a function of moisture saturation, $\hat{\omega}_l$. The relation between p_c and $\hat{\omega}_l$ describes the moisture retention curve, and is determined empirically. Figure 2.3(a) illustrates typical moisture retention curves and Figure 2.3(b) shows example data for different non-salt materials.

Several empirical expressions for this relationship are available in the literature (Brooks and Corey, 1964; van Genuchten, 1980; Kosugi, 1994, 1996) and have been experimentally tested on porous rock and soils. Additionally, porous media in which both air and water are present are known to have water (k_l) and gas (k_g) permeabilities depending on moisture (or gas) saturation, $\hat{\omega}_l$, and are typically less than the respective permeabilities at complete water ($k_{l,\text{sat}}$) or gas ($k_{g,\text{sat}}$) saturation. Given moisture saturation as a function of capillary pressure, it follows relative permeability

Figure 2.3. Typical moisture retention curves showing the relation between capillary pressure and volumetric moisture content or saturation (s).

can be expressed as a function of capillary pressure. Figure 2.4(a) shows the typical variation of the relative water and gas permeabilities, $k_{l,r} = k_l/k_{l,\text{sat}}$ and $k_{g,r} = k_g/k_{g,\text{sat}}$, with moisture saturation. Example data from Corey (1954) are also included in Figure 2.4(b). No experimental data for moisture retention curves and relative gas and liquid permeabilities have been published for salt.

Substituting these constitutive relation into the conservation equations yields strongly non-linear governing equations, which do not lend themselves easily to analytical solution. Except under severe restricting simplifying assumptions, the multi-phase thermoporoelectricity problem must be solved numerically. These equations form the basis of the THMC numerical model CODE_BRIGHT (Olivella et al., 1995) as mentioned in Chapter 3.

Figure 2.4. Typical variation of relative liquid and gas permeabilities with capillary pressure and moisture content or relative saturation.

	<i>Mechanical</i>	
$\boldsymbol{\varepsilon}$	solid strain tensor	-
$\boldsymbol{\tau}$	solid total stress tensor	Pa
ν	Poisson's ratio	-
G	bulk shear modulus	Pa
K	bulk modulus	Pa
K_f, K_s	fluid/rock bulk modulus at constant temperature	Pa
K_m	rock bulk modulus at constant pressure	Pa
B, η_0	Skempton's/Biot-Willis coefficients	-
β_p	fluid compressibility at constant temperature	Pa^{-1}
β_f, β_s	fluid/solid thermal expansion coefficient at constant p/σ	K^{-1}
$\varepsilon_{kk}, \varepsilon_f$	bulk/fluid volumetric strain	-
σ_{kk}	mean normal stress	Pa
ρ_f, ρ_s	fluid/solid density	$\text{g}\cdot\text{m}^{-3}$
	<i>Hydraulic</i>	
p	fluid pressure	Pa
ϕ, ϕ_o	porosity/reference porosity	-
$\mathbf{v}_f, \mathbf{v}_s$	average fluid/solid linear velocity vector	$\text{m}\cdot\text{s}^{-1}$
$\mathbf{q}_f$	Darcy flux	$\text{m}\cdot\text{s}^{-1}$
S_p	storage coefficient for pore pressure changes	Pa^{-1}
ζ	increment of fluid content	-
$\mathbf{k}$	solid permeability tensor	m^2
μ	dynamic viscosity	$\text{Pa}\cdot\text{s}$
g	gravitational acceleration	$\text{m}\cdot\text{s}^{-2}$
z	elevation relative to arbitrary datum	m
Λ_t	Dufour coefficient	$\text{m}^2\cdot\text{s}^{-1}\cdot\text{K}^{-1}$
Λ_h	Soret coefficient	$\text{m}^2\cdot\text{s}^{-1}$
$\hat{\omega}_l, \hat{\omega}_g$	liquid and gas relative saturation	-
$k_{l,r}, k_{g,r}$	liquid and gas relative permeability	-
	<i>Thermal</i>	
θ	temperature	K
$\mathbf{q}_h$	conduction heat flux	$\text{W}\cdot\text{m}^{-2}$
$c_{v,f}, c_{v,s}$	fluid/solid heat capacity at constant volume	$\text{J}\cdot\text{g}^{-1}\cdot\text{K}^{-1}$
κ_f, κ_s	fluid/solid thermal conductivity	$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
R_b	heated borehole radius	m
$q_{h,0}$	applied heat flux at borehole	$\text{W}\cdot\text{m}^{-2}$
	<i>Brine Inclusions</i>	
n	brine inclusion volume per bulk salt volume	-
$\mathbf{v}$	single brine inclusion velocity vector	$\text{m}\cdot\text{s}^{-1}$
C_ℓ, C_s	salt molar concentration in brine/solid	$\text{g}\cdot\text{m}^{-3}$
C_E	salt equilibrium solubility in brine	-
D	salt diffusion coefficient in brine	$\text{m}^2\cdot\text{s}^{-1}$
d_g	effective brine inclusion diameter	m

Table 2.1. Physical Parameters

		<i>Dimensionless Physical Quantity</i>
t_D	$t\mu S_p/(R_b^2 k_1)$	hydraulic time
t_D^*	$t\rho c_v/(R_b^2 \kappa)$	thermal time
$\mathbf{x}_D$	$\mathbf{x}/R_b$	spatial coordinate
∇_D	∇R_b	gradient operator
p_D	pS_p/β_D	pressure
$\sigma_{kk,D}$	$\sigma_{kk}S_p/(\eta_1\beta_D)$	mean normal stress
θ_D	$\theta\kappa/(q_{h,0}R_b)$	temperature
β_D	$\phi_0 q_{h,0}R_b(\beta_f - \beta_s)/\kappa$	thermal expansion coefficient
$\hat{z}_D$	$z\rho_f g S_p/\beta_D$	elevation head
Z	$\eta_2 S_p/[\eta_1 \phi_0 (\beta_f/\beta_s - 1)]$	thermal structural load
U	$3R_b\phi_{inc}/(2d_g\beta_D)H(2-H)$	brine inclusion source strength
		<i>Dimensionless Ratio</i>
α_D	$\kappa\mu S_p/(k_1\rho c_v)$	diffusivity ratio
$\mathbf{k}_D$	$\mathbf{k}/k_1$	hydraulic conductivity anisotropy ratio
$\Lambda_{t,D}$	$\Lambda_t q_{h,0}R_b/(\kappa\beta_D\alpha_f)$	brine thermal/pressure gradient ratio
Pe	$\beta_D/\alpha_{D,f}$	Péclet number (heat conduction/convection ratio)

Table 2.2. Dimensionless Quantities

Chapter 3

Brine Flow Solutions in Salt

In this chapter we discuss some analytical and numerical solutions to the governing equations laid out in Chapter 2. We list a few current and historic numerical models, and list some brine flow modeling benchmark exercises.

Real-world data is needed to parametrize both analytical and numerical models. Gevantman (1981) presented extensive tables of laboratory-derived physical, thermal, chemical, mechanical, optical, and electrical properties of geologic salt. Isherwood (1981) presented summaries of most investigated geologic salt sites in the US, including both geomechanical and hydrologic data. Mellegard and Munson (1997) and Pfeifle and Hansen (1998) presented extensive databases of WIPP-derived mechanical and hydrologic properties of halite and anhydrite inferred from laboratory testing. Pfeifle et al. (1983) presented results of geomechanical testing salt from four locations (Richton Dome, Vacherie Dome, Permian Basin, and Paradox Basin). These databases can be supplemented by recent testing results from German salt research programs (e.g., Wieczorek et al. (2010)).

Analytical Models

We present analytical solutions derived for isothermal (poroelasticity) and non-isothermal (thermoporoelasticity) problems.

Isothermal flow to a nondeforming borehole

In the limiting isothermal flow case with no deformation, the governing equations outlined in Chapter 2 reduce to the well-know diffusion equation

$$\frac{\partial p_D}{\partial t_D} = \mathbf{k}_D \nabla_D^2 p_D, \quad (3.1)$$

where $p_D = p/P_c$, $t_D = t\alpha_f/R_b^2$, and $\mathbf{k}_D$ is the permeability anisotropy tensor. Many solutions exist to this problem for various boundary conditions at the borehole, including constant flowrate and constant pressure conditions. McTigue (1993) presented a solution to this problem for 1D radial

flow with initial and boundary conditions

$$p_D(r_D, t_D = 0) = \lim_{r_D \rightarrow \infty} p_D(r_D, t_D) = 1, \quad (3.2)$$

where $r_D = r/R_b$ and

$$p_D(r_D = 1, t_D) = 0, \quad (3.3)$$

where the characteristic pressure is set to $P_c = p(r, t = 0)$. The solution is given by

$$p_D(r_D, t_D) = -\frac{2}{\pi} \int_0^\infty \frac{e^{-t_D x^2}}{x \Delta_0} [J_0(x r_D) Y_0(x) - Y_0(x r_D) J_0(x)] dx \quad (3.4)$$

where x is a dummy integration variable, $\Delta_0 = J_0^2(x) + Y_0^2(x)$, and (J_n, Y_n) are the n -order, first and second kind Bessel functions (McLachlan, 1955). This model was used by McTigue (1993) and Beauheim et al. (1997) to model brine flow to boreholes in bedded WIPP salt to estimate formation permeability and hydraulic diffusivity. The integration in equation (3.4) should not be evaluated directly with numerical quadrature, as the integrand is singular at $x = 0$. McTigue (1993) discussed approximations to evaluate the singularity. The solution was extended by Gelbard (1992) to include nearby excavation effects on flow toward in borehole using 2D cylindrical coordinates with negligible tangential flow.

Non-isothermal flow to a nondeforming borehole

McTigue (1986, 1990) and McTigue and Nowak (1988) combined thermoelasticity (solid expansion due to heating) with poroelasticity (deforming porous rock coupled with liquid flow), to develop solutions to thermoporoelastic problems relevant to radioactive waste disposal in salt. The thermoporoelasticity problem discussed in Chapter 2 was solved by using the following simplifying assumptions:

- Homogeneous and isotropic porous medium,
- Negligible brine inclusion contribution to total fluid flux,
- Constant mean normal stress ($\sigma_{kk} = \text{const}$),
- Heat flow by conduction only ($\text{Pe} \rightarrow 0$),
- Negligible effect due to borehole ends or nearby excavation (1D radial flow), and
- Radial fluid to finite-radius heated borehole.

Under these assumptions, it can be shown (McTigue, 1990) equations (2.33) and (2.38) simplify to

$$\frac{\partial p_D}{\partial t_D} = \frac{1}{r_D} \frac{\partial}{\partial r_D} \left(r_D \frac{\partial p_D}{\partial r_D} \right) + \frac{\partial \theta_D}{\partial t_D}, \quad (3.5)$$

for the pore pressure field, and

$$\frac{\partial \theta_D}{\partial t_D^*} = \frac{1}{r_D} \frac{\partial}{\partial r_D} \left(r_D \frac{\partial \theta_D}{\partial r_D} \right), \quad (3.6)$$

for the temperature field, where $t_D = t/T_c$, $t_D^* = \alpha_D t_D$, $T_c = R_b^2/\alpha_f$, $r_D = r/R_b$, $\alpha_D = \alpha_h/\alpha_f$, $P_c = b\Theta_c$, $\Theta_c = q_{h,0}R_b/\kappa$, and

$$b = \frac{4GB(1+\nu_u)}{9(1-\nu_u)} \left[\beta_s + \frac{B(1+\nu_u)(1-\nu)}{2(\nu_u-\nu)} \phi_0(\beta_f - \beta_s) \right].$$

Under the assumption $Pe \rightarrow 0$ the heat conduction equation can be solved independently of the fluid flow equation. The coupling between heat and fluid flow appears simply as a time-dependent source term in the fluid flow equation (rightmost term in equation (3.5)).

For homogeneous initial and farfield boundary conditions,

$$\theta_D(r_D, t_D = 0) = \lim_{r_D \rightarrow \infty} \theta_D(r_D, t_D) = 0, \quad (3.7)$$

and a constant heat flux condition at the borehole,

$$\left. \frac{\partial \theta_D}{\partial r_D} \right|_{r_D=1} = -1, \quad (3.8)$$

the solution for the temperature field is well known (McTigue, 1990; Carslaw and Jaeger, 1959). We repeat the solution in nondimensional form for completeness:

$$\theta_D(r_D, t_D^*) = -\frac{2}{\pi} \int_0^\infty \frac{1}{x^2 \Delta} \left(1 - e^{-t_D^* x^2} \right) [J_0(xr_D)Y_1(x) - Y_0(xr_D)J_1(x)] dx \quad (3.9)$$

where x is a dummy integration variable and $\Delta = J_1^2(x) + Y_1^2(x)$. The corresponding solution for fluid pore pressure, obtained by McTigue (1990) using homogeneous initial and boundary conditions

$$p_D(r_D, t_D = 0) = p_D(r_D = 1, t_D) = \lim_{r_D \rightarrow \infty} p_D(r_D, t_D) = 0, \quad (3.10)$$

is repeated in nondimensional form

$$p_D(r_D, t_D^*) = \frac{\alpha_D}{\alpha_D - 1} [\theta_D(r_D, t_D^*) - \vartheta_D(r_D, t_D^*)], \quad (3.11)$$

where

$$\vartheta_D(r_D, t_D^*) = -\frac{2}{\pi} \int_0^\infty \frac{1}{x^2 \Delta} \left(1 - e^{-t_D^* x^2} \right) \frac{\Phi_1 J_0(\sqrt{\alpha_D} x r_D) - \Phi_2 Y_0(\sqrt{\alpha_D} x r_D)}{J_0^2(\sqrt{\alpha_D} x) + Y_0^2(\sqrt{\alpha_D} x)} dx, \quad (3.12)$$

$$\Phi_1 = J_0(\sqrt{\alpha_D} x) \Psi_1(x) + Y_0(\sqrt{\alpha_D} x) \Psi_2(x), \quad (3.13)$$

$$\Phi_2 = J_0(\sqrt{\alpha_D} x) \Psi_2(x) - Y_0(\sqrt{\alpha_D} x) \Psi_1(x), \quad (3.14)$$

$$\Psi_1(x) = -\frac{2}{\pi x}, \quad (3.15)$$

and

$$\Psi_2(x) = J_0(x)J_1(x) + Y_0(x)Y_1(x). \quad (3.16)$$

Equations (3.9) and (3.11) describe the temperature and pressure fields associated with radial flow toward a non-deforming borehole heated at constant heat flux. The integrals in equations (3.9) and (3.12) must be evaluated with similar precautions to equation (3.4), due to integrand singularities at $x = 0$.

Numerical Models

Analytical (and semi-analytical) solutions are limited to linear constitutive models (e.g., elasticity, but no plastic salt creep), heat conduction (i.e., no free convection), and constant formation parameters (e.g., no thermal effects on brine viscosity). To consider these non-linear effects, we must use iterative numerical models.

There are a range of different degrees to which physically coupled processes can be simulated in a numerical model, from loosely to tightly coupled. Two independent models can be run sequentially (e.g., thermal and structural models), computing parameter dependence between the models as a processing step between each iterative model run. This approach works best when coupling is one way or weak (e.g., the thermal problem affects the mechanical problem, but the mechanical problem does not cause significant thermal changes). A single model can alternatively pose the solution of all the equations simultaneously, in a single large matrix. This tight coupling is often the best way to model the problem, but existing specialized codes cannot be used. The coupling of multiple linear problems does not require iterative solution, but iteration may be a solution strategy to the coupled problem. Non-linear parameter dependence on system state always requires iteration (e.g., free convection or multi-phase flow).

Model non-linearities

Unlike analytical solutions, numerical models often allow non-linear relationships between material parameters and the dependent variables we are solving for. In THMC modeling of salt repositories, the following relationships are often considered in non-linear numerical models:

- buoyancy-driven convection, $\rho_f(\theta)$
- temperature-dependent thermal conductivity, $\kappa(\theta)$ (Moss and Haseman, 1981)
- temperature-dependent fluid viscosity, $\mu(\theta)$ (Nowak and McTigue, 1987, §4.4)
- capillary pressure-dependent porous medium saturation, $\hat{\omega}_l(p)$ (Figure 2.3(a))

- saturation-dependent relative fluid and gas permeability, $k_{l,r}(\hat{\omega}_l)$ (Figure 2.4(a))
- stress-dependent salt porosity, $\phi(\boldsymbol{\tau})$ (see next section)
- porosity- and stress-dependent intrinsic permeability, $\mathbf{k}(\phi, \boldsymbol{\tau})$ (see next section).

Salt permeability as a function of mechanical properties

The relationship between rock intrinsic permeability (k), rock porosity (ϕ), and the stress-strain state and history of the rock is very important to brine flow, but it is difficult to characterize in a general manner. Pore structure is the link between the mechanical and hydrologic responses of a porous medium (Stormont et al., 1991b). Several attempts have been made to parametrize the flow system dependence upon the deformation resulting from mechanical deformation. Most attempts fit relatively simple functions to observed laboratory data. Appendix C discusses brine and gas permeability testing in more detail.

The Kozeny-Karman relationship between porosity and permeability (derived for a bundle of cylindrical tubes) is typically used in crushed salt and granular media (Dullien, 1992, §3.3.1)

$$k = \frac{C\phi^3}{\Upsilon S_v(1 - \phi^2)}, \quad (3.17)$$

where C is a particle shape factor, Υ is related to medium tortuosity, and S_v is medium specific surface area. Porosity is nearly as difficult to estimate as permeability, but changes in porosity can be related to changes in rock damage.

Reynolds and Gloyna (1960) developed an empirical relationship between permeability and a combination of stress and pressure, based on fitting experimental data collected from tests on Grand Saline salt dome samples. Their relationship is

$$k_L = a_1 \sigma_m^{-0.212} \quad (3.18)$$

where $\sigma_m = \sigma_2 - p$ is the net confining stress, σ_2 is mean confining stress, and $a_1 = 7.1 \times 10^{-10}$ [m²·psi⁻¹] is a unit-conversion constant. Their k_L was “nonreactive fluid permeability”, most closely approximated through permeability tests with kerosene. Brine permeability was approximately $k_L/3$ in their tests.

Lai (1971) gave the following empirical relationship for salt kerosene permeability

$$\log(k) = 0.62 - a_2 \sigma_m + a_3 \tau_o \quad (3.19)$$

where τ_o is the octahedral shear stress, $a_2 = 6.7 \times 10^{-4}$ [psi⁻¹], and $a_3 = 1.39 \times 10^{-3}$ [psi⁻¹]. Equation (3.19) is visualized in Figure 3.1, it extends (3.18) beyond hydrostatic tests, to include shear (deviatoric) stress effects on salt damage and permeability.

Stormont and Fuenkajorn (1993) based their model upon the equivalent channel concept, developing the following relationship for bulk permeability

$$k = A(\sigma_{3,D})^{2\lambda} \hat{\epsilon}_{kk}^s, \quad (3.20)$$

Figure 3.1. Permeability as a function of net confining pressure (σ_m) and octahedral shear stress (τ_o) (Lai, 1971).

where $\sigma_{3,D} = \sigma_3/p$ is the dimensionless minimum principal stress, $\hat{\epsilon}_{kk}$ is the dilatant volume strain (dilation), λ is a negative exponent, s is related to flow-path tortuosity, and A is a constant. Figure 3.2 shows k and $\hat{\epsilon}_{kk}$ data this model was developed to explain. Equation (3.20) is simplified from the model presented in Stormont et al. (1992).

Figure 3.2. Permeability and dilatant volumetric strain in WIPP salt (Hansen, 2003).

Chan et al. (2001) developed a two-part expression for permeability, which included contributions from salt porosity associated with the intergranular porosity, and a damage-induced microc-

rack network. They implemented

$$k = C_P - \varepsilon_{kk}^3 + \frac{C_{CK}\phi^3}{(1 - \phi)^2}, \quad (3.21)$$

where C_P and C_{CK} are coefficients to estimate from test data. The microcrack contribution was based on results from percolation theory and the cubic law (Peach, 1991), while the contribution due to the inherent intergranular porosity was related to equation (3.17). They found the contribution due to microcracks was more significant, when analyzing WIPP data. Alkan (2009) developed an updated relationship between permeability and dilatancy, based upon percolation theory and the cubic law.

Cook (1987) points to studies where the flow in fractured rocks has shown to deviate from cubic law predictions at low flowrates and small apertures ($\leq 10 \mu\text{m}$). These apertures would be characteristic of salt outside the disturbed rock zone.

In attempts to couple the mechanical and hydrologic systems, permeability or porosity has been related to net confining stress, octahedral shear stress, and dilatant volume strain. Another strategy has utilized relationships developed to describe the reconsolidation of crushed salt, attempting to unify the treatment of crushed and intact salt (Callahan, 1999; Olivella and Gens, 2002). All these relationships are purely empirical.

Ideally, the permeability and porosity changes which characterize the disturbed zone surrounding and excavation would be included in numerical models as a response to mechanical changes. Most numerical brine flow models simply assign higher permeability or porosity to a zone surrounding the excavation.

Current numerical models

The following codes are indicative of different solution methods for coupled sets of non-linear equations using space discretization and an iterative solver.

- Coupled THM finite element codes used for porous media flow:
 - CODE_BRIGHT is a variably saturated deforming porous medium flow finite element model developed at Universitat Politècnica de Catalunya to solve the poroelastic partially saturated brine flow problem in salt (Olivella et al., 1994, 1995).
https://www.etcg.upc.edu/recerca/webs/code_bright
 - FEHM is a variably saturated porous medium flow model considering solute transport and thermal energy balance. The code has limited (infinitesimal deformation) structural modeling capabilities (Zyvoloski et al., 2011).
 - TOUGH-FLAC is a set of tightly coupled independent models, which has been used in enhanced geothermal reservoir simulations, CO₂ storage, and modeling earthquake swarms (Rutqvist, 2011).

- Multi-physics simulators are generally flexible enough to include salt repository relevant THM processes and conditions:
 - SIERRA Mechanics is a general multi-physics finite element code suite (Stewart and Edwards, 2003). It has been used to simulate large deformations under salt repository conditions (Clayton et al., 2010).
 - ELMER is an open source general multi-physics finite element code suite developed by the Finnish Center for Science in Fortran90. It can simulate coupled equations and accommodate large mesh deformations.
<http://www.csc.fi/english/pages/elmer>
 - FiPy is an open source general multi-physics finite volume simulation suite developed by National Institute for Standards and Technology in Python. It can handle coupled and non-linear equations, but it cannot accommodate mesh deformation (Guyer et al., 2009).
<http://www.ctcms.nist.gov/fipy/>

Historic coupled mechanical and flow models

In the following models, the fluid-flow problem was typically a post-processing step performed on the geomechanical modeling results (except for STEALTH/SNEAKY). These mechanical models often consider a wide range of creep deformation and healing constitutive models, allowing more realistic geomechanical modeling.

1. STEALTH (2D & 3D) or SNEAKY (1D): This finite-difference model was a generally coupled multi-phase THM model implemented using the STEALTH modeling framework (for nuclear reactor safety), or as SNEAKY – a stand-alone one-dimensional model (Hart, 1981; Hart and St. John, 1986). Model test cases included near-field heated salt repository conditions with backfill and a DRZ (Gupta et al., 1987).
2. VISCOT + BISCITS: This loosely coupled code pair included a modified version of SUTRA, which is a density-dependent variably saturated flow and thermal transport finite-element code by the US Geological Survey (Wallace et al., 1990).
3. SPECTROM-32 + TOUGH28W: This loosely coupled code pair included a modified version of TOUGH2/EOS8, which is a density-dependent variably saturated flow and thermal transport finite-volume code by Berkeley National Laboratory (Freeze et al., 1997).
4. JAS3D + TOUGH28W: This loosely coupled code pair use a modified form of TOUGH2/EOS8 – see above item (Statham et al., 1998).
5. FLAC3D: This is a commercial finite-difference geomechanical model by Itasca Consulting Group. Several examples in (Wieczorek et al., 2010) post-processed brine flow estimates from mechanical results.

Historic brine flow models without mechanical effects

The following brine-inclusion models, a vapor transport model, and a diffusion model are mentioned here as a historical footnote

1. BRINE only considered brine inclusion migration (Duckworth and Tuller, 1980);
2. MIGRAIN only considered brine inclusion migration (Claiborne et al., 1980);
3. BRINEMIG only considered brine inclusion migration (McCauley and Raines, 1987);
4. VAPMIG combined brine inclusion migration and evaporation front movement (vapor transport) by Knudsen and bulk diffusion through a porous medium (Olander, 1982);
5. SPECTROM-58 solved a coupled set of equations, including brine inclusion migration and isothermal pressure diffusion through a porous medium (Ratigan, 1984a,b);

Hadley and Faris (1981) and Hadley (1982) developed a mathematical model to predict drying front advancement into a porous medium, using Knudsen and bulk diffusion (similar to VAPMIG without brine inclusion motion). This model was used with mild success to match data from several brine inflow experiments (Shefelbine, 1982).

A mathematical model was developed for the Deaf Smith Draft Environmental Assessment (Gupta et al., 1987), based purely upon curve-fitting a diffusion model to observed brine inflow (Pigford and Chambrè, 1985). This model was criticized for its lack of physical justification (Sherer, 1987, p. v & p. C.92).

Model benchmarking exercises

Munson and Morgan (1986) developed a general parallel calculations framework for code validation and verification exercises, based upon experience gained in benchmarking early WIPP geomechanical calculations.

HYDROCOIN was a multi-stage Swedish-led international groundwater flow modeling code verification effort (1984-1990) which covered different geologies considered for radioactive waste disposal (Cole, 1986; Swedish Nuclear Power Inspectorate, 1992). The three levels addressed model verification to hypothetical cases (Level 1), verification against experiments (Level 2), and model uncertainty quantification (Level 3). At Level 1, Case 5 was two-dimensional density-dependent groundwater flow above a salt dome (Konikow et al., 1997), and Case 6 was three-dimensional steady-state regional flow through a bedded salt formation, designed to resemble the Palo Duro Basin in Texas. HYDROCOIN Level 2 included simulation of both field and laboratory coupled free thermal convection (Cases 1 and 2). HYDROCOIN Level 3 (Case 3) was a refined version of Level 1 Case 6 (regional groundwater flow through Palo Duro-like evaporite sediments), and Case 4 was a refinement of Level 1 Case 5 (density dependent flow over a salt dome).

INTRAVAL was a Swedish-led international model benchmarking exercise conducted as a follow-up to HYDROCOIN. Phase 2 included eleven international test cases, one being simulation of isothermal brine inflow to WIPP boreholes (Beauheim et al., 1997). The analytical solution of McTigue (1993) and two finite-element numerical models were calibrated to best match brine inflow data collected from the small-scale brine inflow test (Finley et al., 1992). The project essentially validated the use of Darcy’s law for isothermal brine flow in salt, although they indicated “coupled hydrological and geomechanical models may provide a better understanding of the system” in their conclusions (Larsson et al., 1997).

Freeze et al. (1997) conducted a comparison between three different modeling approaches to simulate observed results from the WIPP large-scale brine inflow experiment (see Figure 4.17). They compared the ability of two numerical models and an analytical solution (McTigue, 1993) to match observed Room Q inflow data. One numerical model computed brine inflow as a post-processing step to a mechanical damage calculation, and the other used uncoupled mechanical deformation calculations to estimate porosity changes in the finite volume TOUGH2 simulator.

DECOVALEX was a coupled THMC modeling benchmark exercise (1992-2007) for radioactive waste disposal in fractured rock (Tsang, 2009) which did not consider salt or brine flow explicitly.

THERESA was a geomechanical German model benchmarking exercise, which mostly focused on salt behavior in triaxial tests (Wieczorek et al., 2010). Some brine migration aspects were considered, but most models (except CODE_BRIGHT) computed brine migration in a post-processing step, rather than in a coupled poroelastic manner.

Chapter 4

Brine Inflow Testing Review

We discuss historic heated and isothermal brine migration tests in roughly chronological order (see Figure 4.1 for experiment time line). We provide summarizing observations of both in situ and laboratory testing at the chapter end.

We include both in situ and laboratory tests, which collected brine migration data (e.g., brine produced through time). Some important isothermal brine migration tests are also reported, as these are an important simplification of the heated brine inflow problem. Any physically realistic conceptual or mathematical model for brine flow in salt must simulate both isothermal and heated brine inflow to excavations.

Figure 4.1. Time line showing major brine-migration tests discussed in this report. SSBI=WIPP Small-Scale Brine Inflow and MR=WIPP Moisture Release

Early laboratory and in situ brine migration experiments in heated salt were covered in the extensive summary report by Shefelbine (1982), while Gnirk et al. (1981) similarly reviewed laboratory testing related to intracrystalline brine migration under thermal gradients. Isherwood (1979) compiled an annotated brine inclusion bibliography – especially including Russian chemical brine inclusions analysis. The conference proceedings from a 1985 workshop on brine migration in salt

at University of California-Berkeley (Sherer, 1987) includes abstracts, discussions, papers, and slides covering research into salt brine migration related to high-level waste disposal, before most research stopped when Yucca Mountain was selected as the sole resting place for US high-level waste in 1987.

Project Salt Vault

Oak Ridge National Laboratory (ORNL) carried out pre Salt Vault in situ heater experiments in the Hutchinson Carey salt mine during July–August 1962 in two 25.4-cm diameter boreholes (Morgan, 1963). One borehole was drilled vertically into the floor, and the other drilled horizontally into a pillar. After 2 days of heating at 3.5 kW, the heaters were operated at 5 kW for a month, reaching maximum borehole wall temperatures of 350° C. Decrepitation was observed in these heated boreholes, at approximately 280° C, accompanied by pulses of water (15.5 L from the vertical borehole and 250 mL from the horizontal borehole). Although salt decrepitation was observed earlier in the laboratory, it was not expected to occur in situ (Morgan, 1961, p. 62). The total brine collected from these boreholes was greater than the brine content contained inside the 290° C contour. The additional brine was attributed to flow through cracks in the salt. It was also noted that decrepitation did not noticeably affect salt heat transfer (Morgan, 1963, p. 30). Based the experience gained from these borehole decrepitation tests, it was proposed to keep design repository conditions below 200° C (“a conservative upper allowable temperature for salt” (Bradshaw and McClain, 1971, p. 7)), a guideline still followed today.

A four-phase prototype hole liner test was conducted in Room 5 of the Lyons, Kansas Carey Salt Mine, beginning in June 1964 (Morgan et al., 1965, p. 15). This test was an operational dry-run using a single 30.5-cm diameter heated borehole, before the larger-scale heater tests were begun the next year. In the first 10 days of heating, approximately 1 L of brine flowed into the borehole, as the salt temperatures approached 200° C. In total, 2.5 L of brine was collected during the 48-day phase I test; collected brine was heavily laden with stainless steel corrosion products. Beginning November 9, 1964, phase II collected 0.66 L of brine over 100 days of heating. Beginning January 26, 1965, Phase III lasted 50 days. Phase III only operated the brine collection system for 1 hour in the middle of the test, resulting in 40 mL of brine. After repairing the hole liner, which broke off down hole during Phase II, Phase IV started June 2, 1965 and did not monitor brine inflow amounts. In all test phases, brine was mostly derived from shale interbeds in the salt.

The earliest well-documented in situ heated brine migration experiments were conducted during 1965–1967 as part of Project Salt Vault by ORNL at the Carey Salt Company mine in Lyons, Kansas (Bradshaw and McClain, 1971, §11.2). Brine accumulation was monitored in three sets of seven vertical 30.5-cm diameter boreholes fitted with both heaters and radioactive sources (adjusted to initially be 10.5 kW total power between electrical and radiation sources). During test design, there were some difficulties quantifying brine inflow, due to the high mine humidity (40–60% relative humidity) and the relatively low brine production rate in salt layers. After attempting several condensation trap types, dry nitrogen gas was found to work best for collecting brine inflow (Bradshaw and McClain, 1971, §10.5.2). The set of seven boreholes in Room 5 had extensive

(a) during heating

(b) during cooling

Figure 4.2. Project Salt Vault brine inflow observations in vertical 30.5-cm diameter heated boreholes (Bradshaw and McClain, 1971, §11.2)

shale and anhydrite interbeds which led to higher brine inflow rates (see Figure 4.2(b)).

A large increase in brine inflow was observed when heater power was abruptly increased (see “40% POWER INCREASE” on January 23, 1967 in Figure 4.2(a)) or decreased (see “MISCELLANEOUS POWER OUTAGES” for Room 1 in Figure 4.2(a) or all three curves in Figure 4.2(b)). The observed water release after turning off the heaters was believed due to the reduced tangential compressive stress, caused by thermal gradient reversal near the borehole.

Slightly more brine inflow was collected in Room 1 after power outages in May 1966, compared to the geologically similar Room 4. This difference potentially contributed to salt radiation hardening in Room 1 (Bradshaw and McClain, 1971, §11.1.4), as the two rooms’ thermal responses were insignificantly different (Bradshaw and McClain, 1971, §11.3.2). Both the significant inflow observed in reaction to heater shutdown and the large quantity of brine inflow in Room 5 (35 L, despite 6 months less heating than Rooms 1 and 4) were unexpected (Bradshaw and McClain, 1971, §11.2). There is some uncertainty associated with the brine collection system in Room 5; it has been proposed some brine was due to the nitrogen gas source, mine air humidity, or ponded water near the boreholes, rather than the salt in the borehole (Gnirk et al., 1981). Similar large brine inflow amounts were observed at WIPP, where a clay layer intersected heater boreholes.

The Room 5 data should not be suspect simply because large brine volumes were collected.

After the end of heating, samples were tested for total moisture content from boreholes drilled around the heater arrays (Bradshaw and McClain, 1971, §11.2.4.1). Depth-averaged samples at least 0.6 m from a heater had water content approximately equal to unheated salt (0.50 vol-%). Depth-averaged samples within 15 cm of a heater had lower water contents (0.31 vol-%), as did all samples from the horizontal plane corresponding to the heater midplanes (0.31 vol-%). These reductions conceptually agree with the brine source being the salt immediately surrounding the boreholes and heaters (see Appendix A for more about representative salt brine content values).

Project Salt Vault also included early laboratory tests on brine migration related to geologic salt, discussing intergranular fluid inclusions movement under a thermal gradient (Bradshaw and Sanchez, 1969). This early brine-inclusion migration publication fit a simple diffusion model to observed inclusions movement in 2.5-cm samples. They modified a model previously developed to describe brine movement in ice crystals under a thermal gradient (Hoekstra et al., 1965).

Project Salt Vault included the first large-scale in situ brine inflow test in salt. It included the first in situ observation of salt decrepitation (1962) and significant brine inflow after heater shut-down (1967). The shale interbeds in Room 5 were the reason for the high brine volume collected there – due to their increased water content and permeability relative to pure salt. The data from Room 5 have been considered suspect, but the Room 1 and Room 4 data were in general good.

Avery Island

Beginning in 1977, experiments were performed at the Avery Island salt mine, operated by the International Salt company near New Iberia, Louisiana. At Avery Island, several in situ tests were conducted by the Office of Nuclear Waste Isolation (ONWI) related to high-level heat-generating waste disposal in salt, including two brine migration studies (Stickney and Van Sambeek, 1984). A brine migration and tracer test was performed by RE/SPEC (Krause, 1983), while another experiment was performed by Sandia National Laboratories (SNL) to test equipment and procedures eventually used in Southeastern New Mexico (Ewing, 1981a). Avery Island is a salt dome with approximately 0.022 wt-% water content (Roedder and Bassett, 1981).

RE/SPEC Avery Island in situ tests

Krause (1983) reported a suite of three brine migration tests performed at Avery Island beginning in June 1979, including subsequent post-test laboratory analysis (see Figure 4.3(a) for results). An ambient thermal condition brine migration test (site AB), and two heated brine migration tests were performed (sites NB and SB). The three sites each consisted of the same seven-borehole set: a central 7.6-cm heater borehole, and pairs of 3.8-cm boreholes at 5, 10, and 20 cm radial distances out from the central bore. At each radial distance (but different angles) there was both a thermocouple and brine borehole. In the AB test, nothing was put in these peripheral boreholes. In the

NB test, the brine boreholes had glass beads and packers and were initially pressurized. In the SB test, the brine boreholes had synthetic tagged brine in the glass beads, initially pressurized using a packer system to 690 kPa. Both the NB and SB sites used 1-kW resistive heaters. Maximum borehole wall temperatures were approximately 50° C at both the SB and NB sites.

Figure 4.3. Avery Island RE/SPEC brine inflow test (Krause, 1983)

Approximately half the total brine inflow to Site SB occurred during the cool-down period. No brine migration data were collected during the cool-down period at Site NB. In conjunction with brine collection, nitrogen gas-permeability tests were conducted (Figure 4.4(a)). The salt permeability was observed to increase by as much as five orders of magnitude ($1.2 \times 10^{-16} \text{ m}^2$ from $2.0 \times 10^{-21} \text{ m}^2$), comparing tests at the end of cooling to pre-test results. Permeability tests before the heating phase of the brine migration experiment began (July 29, 1979), indicated the gas permeability to be approximately 2.5×10^{-21} .

Heater tests were also conducted at Avery Island (Stickney and Van Sambeek, 1984), and extended gas permeability tests were conducted in boreholes surrounding heater Site C from December 1980 to March 1981 (Blankenship and Stickney, 1983). Both constant-head and falling-head gas permeability tests were conducted, with good agreement in results from the two different methods (see Appendix C for more discussion related to gas permeability testing in salt). The results from these tests can be used to qualitatively estimate the salt permeability temperature dependence, assuming heterogeneity and stress differences do not have significant effects on the results (Figure 4.4(b)). The results showed salt permeability was several orders of magnitude lower in boreholes drilled closer to the central heater, which were hotter. It was hypothesized thermal salt crystal expansion effectively closed off the intercrystalline porosity.

Taking together the Site C permeabilities during heating, and the Site SB permeabilities during

Figure 4.4. Avery Island heated salt permeability test results (Krause, 1983; Stickney and Van Sambeek, 1984)

cooling, salt permeability decreased during active heating and increased during post-test cooling. The pre-test and end-of-heating permeabilities were similar (10^{-21} m^2) and lower than other recorded values away from the heaters.

Site SB involved conservative tracers (D_2O and Mg) in a nearby borehole (Figure 4.3(b)). A region surrounding the heater and tracer boreholes was excavated with a 40-cm overcore and subsequently analyzed (Figure 4.5). Results showed D_2O levels above background on both the hotter and cooler sides of the brine borehole. In post-test analysis, D_2O was observed in the desiccant canisters, indicating the tagged brine flowed into the heated borehole. The results from Site SB at Avery Island are unique, since they represent the only in situ brine tracer test ever conducted in salt with spatial concentration distribution data (heated or isothermal).

The RE/SPEC brine inflow tests at Avery Island were designed to provide data for the brine inclusion migration model of Jenks (1979). Krause (1983, p. 52) stated:

The observations related to Mg and D_2O concentration and microcrack induced flow are not really succinctly related to single crystal brine inclusion migration which was the original intent of the suite of experiments. Our findings and observations, related to specific chemical concentrations near the heater borehole, indicate that under moderate temperature levels and low temperature gradients, D_2O (in HDO form) could move via porous media type flow into a heated region of salt. As evidenced by the post-test D_2O concentration, shown in [Figure 4.5], the heating of the salt matrix in the heater borehole region may have caused sufficient opening of the grain boundaries to provide flow pathways for small amounts of tagged synthetic brine to move preferentially toward the heater borehole. Additionally, evidence for porous media type flow is enhanced because brine boreholes (B2 and B4) were pressurized during the Site SB test. The heater borehole was not pressurized, therefore, a pressure differen-

Figure 4.5. D₂O laboratory Results at Avery Island brine migration Site SB in over-cored salt (Krause, 1983).

tial could cause an added mechanism for D₂O to move toward the heater borehole. Thus, the large-scale inclusions (the brine boreholes) are reservoirs for a fluid to move into another region by either thermal or piezometric potentials.

The excellent quality data collected from the unique in situ tests conducted at Avery Island provide an indication of salt permeability changes during and following heater tests. The distribution of D₂O at Site SB supports intergranular brine transport under a pressure gradient (the thermoporoelasticity model of McTigue (1986, 1990)).

SNL Avery Island in situ tests

October 1979 through March 1980, Ewing (1981a) performed a heated brine inflow test using a 9-element quartz-lamp heater, monitoring brine inflow to the heater borehole. This test was largely to confirm equipment and technique viability, but the data collected during testing was also reported.

The results collected from the 2-kW SNL test confirmed the observed spikes in brine inflow at the beginning and end (140 days) of heating, with approximately 53 grams of total brine inflow to a 12.7-cm borehole at 200° C. The majority of this brine collection (46 g) may be attributable to drying out the upstream desiccant cartridge between the nitrogen supply tank and the brine collection borehole. It was estimated 6 g of brine could be attributed to the salt.

Only 1.68 g of brine inflow is reported during the cool-down period, but only 24 hours of

brine inflow data is reported after heating stopped. The largest single brine inflow accumulation in the RE/SPEC Avery Island tests (10.55 g) occurred between August 29 and September 2, 1980 (Figure 4.3(a)) – more than one day after complete heater shutdown, and more than 5 days after beginning step-down from 100% power. It is likely a significant amount continued to flow to the borehole in the SNL Avery Island test (at possibly increasing rates) after brine inflow measurements stopped.

The SNL Avery Island brine inflow test was mostly to verify equipment, determining if quartz-lamp heaters were feasible (as opposed to bulkier resistive heaters), before using them in southeastern New Mexico. The brine inflow rate data were not particularly useful, because brine redistributed between the upstream and downstream desiccant canisters.

Mississippi Chemical Company Potash Mine

Two brine inflow tests were conducted in the Mississippi Chemical Company (MCC) potash mine, near Carlsbad. The mine was used as a test bed for equipment and techniques, before the first underground excavations at WIPP occurred in 1981. In situ deformation and waste package testing and samples for other laboratory tests came from the seventh ore zone in the McNutt member of the Permian Salado Formation, stratigraphically above the future WIPP horizon. The salt being tested contained small quantities of polyhalite and other non-salt evaporites, typically totaling just over 10% of the total rock volume (Lambert, 1980). A single-borehole brine inflow test was conducted, similar to the Avery Island test. A three-borehole brine inflow test was also performed, using similar equipment but different thermal loading and timing.

Single-borehole in situ brine inflow test

Ewing (1981b) reported the results from the application of the same instrumentation (quartz lamp heaters) and methods used in the SNL Avery Island brine migration test in the MCC potash mine. Compared to the results observed at the domal salt Avery Island site, significantly more brine inflow was observed, and more fluctuations in power occurred during the test.

The formation was heated to approximately 200° C on the 12.7-cm borehole wall during the test length of 113 days. Approximately 40% of the total water collected was during an over-temperature spike lasting 10 days when the borehole wall temperature reached approximately 270° C (see Figure 4.6). During the overheating incident, the first desiccant canister was “swamped” and an unknown amount of brine was lost and not reported in Figure 4.6. It was believed the large brine pulse was associated with salt decrepitation (Ewing, 1981b).

After the overheating episode, heater power was reduced to 1.5 kW, resulting in approximately 180° C. Three unscheduled power losses were followed by pulses in brine inflow. Significant efflorescences encrusted the heater borehole wall, enough to saturate 188 mL of water. Again, only one day of brine inflow data was collected during post-test cooling.

Figure 4.6. MCC potash mine brine inflow test results (Ewing, 1981b).

The data from the single-borehole brine inflow tests at the MCC potash mine were at the time considered poor due to power fluctuation issues, the overpower decrepitation episode, and the loss of some collected brine. Despite these problems, this was the only instrumented brine inflow test where decrepitation conditions have been observed in situ (during 1962 Salt Vault test only total inflow was measured), and therefore it represents a imperfect but unique data set.

Three-borehole in situ brine inflow test

A second suite of three in situ brine migration tests were performed in 1981 for four months across a range of temperatures in the MCC Potash Mine, to test repeatability and monitor encrustation growth at the borehole wall using video cameras (Shefelbine, 1982). The heater arrangement was reduced from nine to one quartz lamp, but installed into three separate boreholes, separated by at least 1 m of salt. Heater power was controlled in Boreholes A and C to produce borehole temperatures of 90°, 110°, 145°, and 205° C for one month at each level (Figure 4.7).

The heater in Borehole B was located between Boreholes A and C, and was not turned on until the 205° C step at the end of three months. Near the end of each one-month step, inflow rates were observed to decay down to nearly the level observed in the unheated B Borehole. Temperature rises of 2°, 4°, and 7° were observed in Borehole B during power steps in boreholes A and C.

Different brine inflow rates were observed during the 13-day ambient pre-test conditions, indicating some geological or geomechanical heterogeneity existed between the boreholes (2.7, 1.2, and 1.0 g pre-test brine inflow total). In Boreholes A and C, 9.5% and 12.4% of the total brine collected flowed during the post-heating phase. Over 20% of the total brine inflow in Borehole B occurred after heater shutdown, which was only actively heated for one of the four months. It is also likely a significant cool-down phase brine inflow was not captured, since again only 24 hours

Figure 4.7. MCC potash mine three-borehole brine inflow test results. Modified from Shefelbine (1982).

of post-test brine inflow data were collected.

The borehole camera revealed encrustations grew in isolated “spurts”, rather than at constant rates. Encrustations also tended to grow along grain boundaries at the borehole face. The mass of encrustations observed was in general agreement with the total mass of brine collected.

The three-borehole experiment results showed the three boreholes were not thermally isolated. The two similar boreholes did not produce exactly repeatable results, but were in general agreement with one another. The photographic evolution of salt encrustations in the borehole is interesting qualitative evidence for intergranular brine transport – possibly in a discontinuous manner. The results of this test were only reported in Shefelbine (1982). An internal test plan and a few unpublished memos also describe the test layout. The pending project report listed in the references of Shefelbine (1982) was apparently never finished.

WIPP-related Laboratory Brine Inflow Tests

In the late 1970s and early 1980s a series of laboratory experiments of small and intermediate scale were carried out by SNL and RE/SPEC to understand “macroscopic” brine flow in heated salt (Lambert and Shefelbine, 1979). The term “macroscopic” was used to set these tests apart from brine inclusion migration tests being performed in laboratories, typically on heated microscope stages (e.g., Jenks (1979), Machiels et al. (1981), and Olander et al. (1982)). The tests used salt samples from the MCC potash mine, which has higher non-halite salt components than the halite

and argillaceous halite found in the waste disposal horizon at WIPP.

1-kg laboratory test

Hohlfelder (1979a) performed a benchmarking exercise to compare different brine-outflow rate measurement techniques for heated geologic salt samples. Three 5-cm by 10.8-cm salt cylinders from the MCC potash mine were heated for three days to maximum temperatures 165°–250° C to compare three different water loss estimation methods (Hohlfelder and Hadley, 1979).

Figure 4.8. Characteristic water release history for second 1-kg sample (Hadley and Faris, 1981)

The first method simply weighed the sample before and after heating, attributing the difference to water loss. The second method flowed dry nitrogen gas across the sample, collecting moisture in downstream desiccant containers. The desiccant canisters were weighed before and after heating. The third method estimated water loss continuously through calculations using measured humidity, pressure, and nitrogen flowrate.

The results indicated good agreement between the approaches in a laboratory setting (all measurements within 10%). In two of the tests the post-heating brine pulse was also observed, as 5.5 and 9% of the total water loss (the first sample was not monitored after heater shut down). Figure 4.8 shows a typical result from the second experiment, with two heater power levels, their associated peaks in brine inflow rate, and the largest peak associated with the final heater shutdown.

Later brine inflow modeling (Hadley and Faris, 1981) qualitatively matched post-heating brine releases using a step change in formation permeability or porosity at heater shutdown. This in-

crease in permeability or porosity was associated with tensile rock failure during cooling, as predicted by separate uncoupled geomechanical modeling (Trucano, 1981).

Salt Block I/II laboratory tests

Similar cylindrical 1700-kg bedded salt samples from the MCC potash mine were used in two intermediate-scale laboratory tests.

The Salt Block I experiment was carried out from January to April 1977 to determine the stress state and thermal properties of a 1-m cylindrical heated salt block, heated axially (Duffey, 1980). Post-test water content analysis was performed on two 10-cm samples and compared to unheated samples. Temperature data collected during the test showed excellent agreement with modeling, but moisture release results were somewhat inconclusive (slightly less water loss was observed closer to the heater).

The Salt Block II experiment was carried out from November 1978 to April 1979 to determine brine release characteristics of a similar axially heated 1-m cylindrical salt block from the MCC potash mine (Hohlfelder, 1980). The Salt Block II experiment focused on the in situ measurement of temperatures, heat fluxes, and brine movement to facilitate future modeling and benchmarking efforts. The salt block had a bulk composition of halite (88%), polyhalite (8%) and sylvite (4%) (Lambert, 1980).

Figure 4.9. Salt Block II laboratory Setup (Lambert, 1980)

Temperature and heat flux were measured in the crushed-salt backfill surrounding the 1.5 kW heater, throughout the salt block, on its insulated top and bottom surfaces, and on its water-jacketed outer surface. Water release was continuously estimated using dry nitrogen gas passed through the axial heater hole (see Figure 4.9). A maximum 200° C salt temperature was observed near the heater.

Heating and cooling phases were stepped, with spikes in brine inflow observed at each change in heater power. A significant portion (43%) of the 111.4 g of brine was collected during the heater stepdown phase, with the largest jump in brine collection at the reduction from 1600 to 1000 W (Figure 4.10). Two characteristic water mass loss rate behaviors were observed through time at each change in heater power (see Figure 4.10). Steps up in heater power led to increases in brine inflow by a factor of 10. Water loss rate reached a maximum within 1–1.5 days from the beginning of the change, and declined monotonically afterward (with small-amplitude diurnal fluctuations superimposed). Decreases in heater power led to increases in brine inflow by a factor of 50, followed by an abrupt decrease in brine inflow (without the small-amplitude diurnal fluctuations due to a difference in brine flow measurement procedure after day 80, which led to more smoothing).

Figure 4.10. Observed temperature (red) and brine inflow (blue) rate curves and cumulative brine inflow for Salt Block II experiment (Hohlfelder, 1980)

Post-test mineralogical analysis indicated brine inclusions did migrate in the portions of the salt block nearest to the heater, but rarely across grain boundaries (Lambert, 1980). Lambert concludes:

Photomicrographic observations have indicated [the water collected during the Salt Block II experiment] did not originate primarily from intragranular fluid inclusions, which are volumetrically by far the most important contribution to the total water present in the evaporite. ...

The generally restricted movement of intragranular fluid during the 100-day heating phase is consistent with the low rates of individual intragranular fluid inclusion move-

ment reported by Roedder and Belkin (1980), about 1 cm/yr at these temperatures and temperature gradients. . . .

Some of the fluid encountering a grain boundary could become part of the intergranular fluid phase, whose movement would be governed by a different set of mechanisms. The aqueous phase at grain boundaries appears to have been mobilized, and may be the most important mobile moisture source, except within 2 cm of the heater.

Roedder and Belkin (1980) interpreted some results from Salt Block II differently. They contended as much as 179 g of brine (rather than the 111 g published) flowed to the borehole, based on the mass of hydrous minerals on the surface of the block. They also concluded brine inclusions, which were observed by Lambert (1980) as having not moved very far, had in fact moved but not changed shape. The disagreement between Lambert (1980) and Roedder and Belkin (1980) on Salt Block II results became moot, since at the time of these publications WIPP was legally determined to not be the final destination for heat-generating radioactive waste (Powers and Martin, 1993).

The temperature and brine inflow data collected from Salt Block II were generally very good quality. The experimental results include a set of detailed measurements made at an intermediate scale. The results are an example of a complex brine outflow time series which is difficult to collect at the field scale.

(a) McTigue (1990) solution (Sherer, 1987)

(b) Ratigan (1984b)

Figure 4.11. Modeling results for Salt Block II experiment

Observed fluctuations cannot be reproduced with numerical models which only considered brine inclusion migration due to thermal gradients. McTigue (Sherer, 1987, p. C.85–C.90) successfully simulated the first Salt Block II experiment stage (Figure 4.11(a)) using a thermoporoelasticity model which included the finite domain size. The ability of the McTigue (1986) model to explain brine early inflow during the Salt Block II gives some credence to Lambert (1980) assessment. An attempt by Ratigan (1984b) to simulate observed brine inflow from this experiment was less successful. The SPECTROM-58 model included both brine inclusions and intergranular flow, but did not include differential thermal expansion effects on porous media flow. The model had problems matching the early portions of the test with the vapor flow and brine inclusion flow mechanisms (Figure 4.11(b)).

Acoustic emission laboratory test

In the “salt cracker” experiment, two 1.6-kg salt samples from the MCC potash mine were heated to 200° and 300° C respectively, while monitoring sample brine loss and acoustic emissions (Hohlfelder et al., 1981).

Figure 4.12. Temperature, brine release rate, and acoustic emission rate during the heating and cooling phases of the second test (Hohlfelder et al., 1981).

The first sample was not heated past the decrepitation point (approximately 250° C), but it still produced acoustic emissions at changes in heater power. The second sample was heated past the

decrepitation point and produced significant acoustic emissions during decrepitation. The water released by the second sample was 0.4 wt-%, which is similar to other water content estimates for this salt. Both samples produced a large acoustic emissions burst associated with heater shutdown, although these bursts were smaller than those associated with decrepitation in the second sample (Figure 4.12). A 6-minute temporal delay was introduced to brine loss data (compared to the temperature data) by an in-line catalytic converter. The catalytic converter was used to remove hydrocarbons which would alter operation of the dew-point gages used to estimate brine outflow.

In the first sample heated to 200° C, approximately 30% (0.13 g) of the total brine was collected after the end of heating. Although nearly twice the brine was collected during the cooling phase in the second sample (0.24 g), it was only 4% of the total brine collected, due to the large brine release associated with decrepitation.

The acoustic emission source was concluded to be microcrack initiation. The relatively large water release seen following heater power shut-down is therefore caused by increased cracking, leading to increased salt permeability compounded upon fracturing due to decrepitation. The data from this test are excellent examples of high-frequency brine collection and acoustic emission data. Despite the large amount of brine collected during decrepitation, additional brine was also collected during cool down.

RE/SPEC laboratory-scale tests

Laboratory studies were made using over 100 small (250 g) salt samples, applying a systematic program of constant temperatures and thermal gradients to samples, with some post-test petrographic analysis (Krause, 1981). Brine migration results regression analysis (distance moved vs. applied temperature or thermal gradient) indicated approximately 30% of the brine released was more correlated with temperature increases without a significant thermal gradient. The remaining 70% of the brine released was more correlated with the various thermal gradients imposed on the samples.

A “thin-disk” experiment set was also performed as part of this study. The hotter and colder ends of a short cylindrical sample were separately monitored for brine release while a thermal gradient was imposed along the sample axis. Nearly equivalent brine amounts were collected on two sample ends. This observation does not agree with the conjecture that brine inclusions always move towards the heat source. Brine inclusions migration alone would not predict this result unless half the brine inclusions were biphasic (> 10% gas).

WIPP In Situ Brine Migration Tests

A heated brine inflow experiment was carried out in boreholes drilled for the defense high-level waste Thermal/Structural Interactions tests at WIPP in the mid 1980s. In the late 1980s all testing related to defense high-level waste was stopped, only testing related to the transuranic waste WIPP

mission was allowed to continue (Mora, 1999). Isothermal brine inflow studies in boreholes and specially built rooms were carried out through the mid 1990s at WIPP. The WIPP site contractor (initially Westinghouse) also monitored brine weep inflow as part of WIPP operational maintenance since the earliest site design validation excavations in 1982 (Westinghouse Electric Corporation, 1983a).

WIPP in situ moisture release experiment

The WIPP Thermal/Structural Interactions tests in Rooms A1 and B included four heaters without backfill between the heaters and the borehole wall. Annular space was flushed with dry nitrogen and passed through periodically weighed downstream desiccant canisters to measure borehole brine inflow. Rooms A1–A3 were a reference design, with 470-W heaters set in vertical boreholes to produce the heat load expected from a design defense high-level waste repository. Room B was an overtest design, with 1500-W heaters in similar vertical boreholes. Four boreholes were instrumented for brine migration analysis; two 76-cm diameter boreholes in the reference A1 Room (canisters without overpacks), and two boreholes in the overtest B Room (B041 was 91 cm in diameter to accommodate the mild steel overpack, while B042 was 76 cm in diameter, without an overpack).

A few days of isothermal brine inflow data were collected before heaters were turned on in March 1985 (Room B) and October 1985 (Room A1). Heating continued in Room B until January 1989 (although the B042 heater failed in February 1987 (Munson et al., 1990)), and in Room A1 until July 1990 (Munson et al., 1992). Borehole wall temperatures in the two Room A1 heaters had reached an approximate steady-state temperature of 50° C after 100 days of heating. In Room B, the boreholes wall temperature had reached approximately 120° C after 200 days of heating.

The north experimental area, where Rooms A1 and B were located, was stratigraphically above the planned disposal horizon. This was done to ensure heaters placed in vertical boreholes into the floor would be placed adjacent to the layers in the planned disposal rooms. Clay unit “F” and several argillaceous halite intervals intersected the heater boreholes drilled in Rooms A1 and B (similar to DBT boreholes in Figure 4.14).

Brine migration data and preliminary modeling results were summarized in interim reports (Nowak, 1986a; Nowak and McTigue, 1987) and conference papers (Nowak, 1986b; McTigue and Nowak, 1988). All 4 test boreholes produced brine under isothermal conditions at 5 to 15 g/day, prior to the start of heating (Nowak, 1986a). After early transient effects, the 470-W heater boreholes in Room A1 produced brine at approximately 8 g/day per borehole (Figure 4.13), while the 1500-W heater boreholes in Room B produced brine at 50 and 80 g/day per borehole once transient effects had died down (Nowak and McTigue, 1987).

The brine collection systems were originally designed for a maximum brine inflow rate of 20 g/day. The high brine inflow rate in the Room B boreholes (Figure 4.13) initially overwhelmed the system; condensate was observed in the system tubing. The nitrogen mass flow rate was increased, eventually drying out the tubing by day 130. Room B daily brine inflow rates are not

Figure 4.13. WIPP Room A1 (470-W heater) and B (1500-W heater) brine inflow rates (McTigue and Nowak, 1988)

accurate before this time, but it is believed the cumulative mass by day 130 is representative, since no significant brine was lost. Brine inflow rates in Room A1 were initially high, then stabilized at a lower rate. Brine inflow rates in Room B were artificially low at early time, which makes the rates rise for the first 100 days, rather than initially peak and decay as in Room A1.

Nitrogen inflow rates in the Room A1 boreholes were reduced by a factor of four, but brine collection rates were unaffected (Nowak, 1986a; Nowak and McTigue, 1987). This resulted in a quadrupling of the brine partial pressure in the boreholes. The increase in partial pressure did not result in an decrease in brine collection, which is contrary to vapor transport models which depend on the brine partial pressure in the borehole as the driving boundary condition (e.g., Olander et al. (1982) or Hadley and Faris (1981)).

Vertical and horizontal strain data were collected in each borehole, but all gages eventually failed due to gage deterioration problems and strain exceeding the gage limits in Room B at approximately 100 days. Early data showed vertical (axial) expansion and horizontal (circumferen-

tial) contraction at the borehole walls along the vertical length of the heaters (Nowak, 1986a). The only rapid strains were observed 4 days after initial heater activation.

Krumhansl et al. (1991) performed a post-test mineralogical analysis on salts deposited on heater B042, which received most brine and was over-cored using a 94-cm bit during the period February–November 1988. Analysis of the overcored B042 heater and associated salt revealed the air gap had been eliminated between the canister and borehole wall by the salt flowing inward against the canister overpack during heating. A porous discolored weep-deposited salts layer was found between the original borehole wall and canister. Salts associated with 20–23 L of water were present on the canister surface, which agreed with the brine observed during the first 400 days (when the borehole wall reached boiling temperatures).

The WIPP in situ moisture release experiments in Rooms A1 and B collected a large quantity of brine, much more than laboratory tests and preliminary models had predicted. The heaters in Room B operated for nearly 4 years, while those in Room A1 operated for almost 5 years. No brine inflow data were reported during cool-down periods. In general the data were high quality (aside from early Room B brine rate data and late time strain gage data), and showed the effects different heater power levels and Clay F had on the total brine collected.

WIPP small-scale brine inflow tests

Several years of isothermal borehole flow data were collected in 17 WIPP boreholes (Finley et al., 1992). The boreholes were mostly vertical. Out of the four horizontal boreholes, the two Room D boreholes in relatively pure halite (DBT16 & DBT17) did not produce brine (Figure 4.14). The five boreholes in the Room Q access drift floor (QPB01–QPB05) intersected the 0.9-m anhydrite and clay layer MB139, producing the most brine (150 kg of brine over 2 years). The eight vertical boreholes in Room D (DBT10–DBT15, DBT31 & DBT32) only produced 95 kg of brine over 3.5 years. Brine production rates varied significantly between the five Room Q access boreholes (ranging from 2 to 90 kg cumulative inflow per borehole), despite their similarity in construction and proximity (within 2 m distance). The two horizontal boreholes in Room L4 (L4B01 & L4X01) were the least productive flowing boreholes, producing less than 3.5 kg of brine in 2 years.

Most of the 15 boreholes producing brine generally peaked inflow soon after drilling, followed by a slow decay (Figure 4.15). Despite apparent complexities in behaviors and temporal responses, most variability can be explained by geologic heterogeneity. Horizontal boreholes tend to flow less brine because they cut across fewer geologic layers than vertical boreholes (Figure 4.14). Small-scale geologic and excavation-related differences between boreholes likely contribute to further observed differences. The complex temporal histories are more difficult to explain, without geomechanical measurements of borehole closure and salt stress, and formation permeability through time. The data from this test was the focus of the WIPP INTRAVAL modeling benchmark study (Beauheim et al., 1997), described briefly in Chapter 3.

Figure 4.15. WIPP Small-Scale Brine Inflow results through time for vertical boreholes in Room D (Finley et al., 1992)

WIPP large-scale brine inflow test (Room Q)

Room Q was an isothermal brine inflow test mined with a tunnel boring machine in an area isolated from existing WIPP excavations. The final room was a 2.9-m diameter cylinder 109 m long. The Room Q geometry and construction method were chosen to minimize excavation impacts to salt and to reduce stress-induced fracturing associated with rectangular openings. Brine inflow, humidity, pore pressure, permeability, room closure, and disturbed rock zone geophysical properties were collected in Room Q.

Figure 4.16. WIPP Room Q inflow data (Freeze et al., 1997)

Room Q sloped uphill following an orange marker band and clay seam, naturally collecting brine inflow at the room entrance. Different seals (temporary and permanent) were installed at the room entrance to isolate Room Q air and measure total room brine inflow (Figure 4.16). Approximately 5 years after construction, leaks developed through fractures in the salt near the door, which allowed brine to escape unmeasured.

Measured inflow to Room Q was modeled using three different approaches (Freeze et al., 1997). A modified form of TOUGH2 was loosely coupled with a geomechanical model to allow porosity specification at each time step. The isothermal poroelasticity model of McTigue (1993) was used to predict inflow, assuming all flow was due to a thin horizontal anhydrite layer intersecting the room (Freeze et al., 1997, Appendices A2 & A3). Munson et al. (1995) predicted brine inflow to Room Q using a mechanical damage (“snow plow”) model. The damage model was a post-processing step applied to a geomechanical damage calculation. Simulations indicated the DRZ (volumetric strain $\geq 10^{-4}$, comprised of both elastic and inelastic components) formed immediately, extending 0.5 m into the formation after 1 year. Figure 4.17 shows damage estimates at 5 years and brine inflow using the geomechanical snow plow model. For comparison, Appendix B includes model-predicted damage results for of non-circular cross-section rooms.

Figure 4.17. Computed Room Q damage at 5 years (Freeze et al., 1997), and snow-plow model-predicted brine inflow (Munson et al., 1995)

Before Room Q was mined, 15 boreholes were drilled and instrumented to allow pore pressure and permeability testing before and after mining, in a plane perpendicular to the borehole 22.9 m along the room length. These tests provided the best representation of the far-field static formation pressure (≈ 15 MPa) of any borehole tests at WIPP (see QPP intervals in Figure 4.18) (Domski et al., 1996; Beauheim and Roberts, 2002). Brine permeability data were also estimated from these boreholes, and are discussed in Appendix C.

Westinghouse brine monitoring program

When WIPP excavations began in 1982, small brine weeps were observed on excavation walls. Brine studies began with the Site Validation Program (Westinghouse Electric Corporation, 1983a, §10) and were formalized as the Brine Sampling and Evaluation Program (BSEP) in 1985 (IT Corporation, 1995). Eleven years of observations (1982-1993) were summarized in two final reports (Deal et al., 1993, 1995). The BSEP and these reports contended a limited (finite) amount of brine will seep into the WIPP excavations, not including boreholes. Calculations estimated less than 2,000 L of brine would be expected to flow naturally into the WIPP excavations. BSEP data through 1991 are contained in Deal et al. (1993), while the final two years of data and additional analysis are contained in (Deal et al., 1995).

Several short-duration (48-hour) low flowrate (20-30 L/hour) open-hole pumping tests were conducted in 10-cm vertical boreholes completed to MB139, approximately 2 m below the WIPP disposal horizon drift floor (Deal et al., 1995, Appendix E). The tests confirmed connected frac-

Figure 4.18. Static formation pressures interpreted from tests conducted in the WIPP underground (Beauheim and Roberts, 2002)

tured zones exist in MB139 at drift intersections. Aside from this general observation, the tests were largely inconclusive due to the tests' short durations and lack of recovery data. Horizontal displacement was observed in some boreholes at the clay layer near the top of MB139.

In general, long-term monitoring showed significant brine seepage along in a mined room ceases three years after initial mining of the opening, although some small seeps continued for longer periods of time. Brine inflow to boreholes has been observed to remain significant for much longer periods of time than seeps on the walls of rooms (Deal et al., 1994). At one location where seeps had stopped, the wall was mined 1 m back. After mining, seeps formed on the new wall and survived a few more years Deal et al. (1993).

Macroscopic fractures up to several centimeters in width develop parallel to the excavation sides (see damage illustrations in Appendix B). These fractures serve to isolate the salt at the excavation face from the far field, and since they are air filled, they act as barriers to brine flow. Brine weeps isolated from the far field will stop seeping within a few years of excavation. Boreholes penetrate these macroscopic boreholes, accessing salt connected to clay and anhydrite layers, as well as far-field brine sources.

Asse In Situ Brine Migration Tests

The Asse II facility in Germany was the site of several tests related to the heat generating waste disposal in relatively pure domal salt. The salt at Asse has a total water content in the range 0.05–0.25 wt-% (Roedder and Bassett, 1981; Urai et al., 1986; Rothfuchs et al., 1988). In the 1980s, a large-scale heated brine migration test was jointly designed and conducted by ONWI in the United States and GSF in West Germany. In the 1990s, both borehole and in-drift high-level waste emplacement approaches were tested at Asse. These tests involved extensive damaged zone characterization surrounding excavations (see discussion and results in Appendices B and C). More recently, smaller-scale isothermal brine migration tests were conducted to characterize anisotropy and heterogeneity in excavation damaged salt.

Heated brine migration test

A large-scale in situ heated salt test was performed at Asse May 1983 – November 1985. The test setup (including pre-test modeling) is detailed in a design report (Westinghouse Electric Corporation, 1983b), while data and modeling results were summarized later reports (Coyle et al., 1987; Rothfuchs et al., 1988). Many different data types were collected during this test. Thermal, mechanical, hydrologic, chemical, and geophysical data were collected throughout the test, and extensive post-test analysis was done on the salt and disassembled testing equipment. Much less water was collected during the heated test phase (< 200 mL per borehole) than was predicted in planning simulations.

The program consisted of four independent tests in 43.5-cm boreholes, each with eight surrounding guard heaters. Two locations included radioactive ^{60}Co sources (boreholes 3 and 4), and two locations were initially pressurized (boreholes 1 and 3). Central borehole wall temperatures reached an approximate steady-state 200°C after about 200 days of heating. The boreholes open to atmospheric pressure (2 and 4) were flushed with nitrogen gas, collecting moisture in a cold trap. Borehole 3 developed a leak during the test and was converted to an atmospheric pressure test. Extensive room closure and in situ stress measurements were taken before, during, and after the heated test phase.

Comparing brine inflow in Sites 2 and 4 during heating (Figure 4.19(a)), the radioactive Site 4 accumulated brine at a higher rate. More brine was accumulated at Site 4, despite the 200-day head start at Site 2. Radioactive Sites 3 and 4 both accumulated brine at higher rates than non-radioactive Site 2 (Figure 4.19(a)). Radiation effects may contribute to the observed differences. A vapor transport model was used to predict brine transport during the heating phase, with only order-of-magnitude agreement at late time (upper solid line in Figure 4.19(a)).

The majority of the brine was collected during the cool-down test phase in boreholes 2, 3, and 4 (Figure 4.19(b)). Borehole 1 remained at approximately 3.25 bars (1.5 bars computed brine vapor partial pressure) until it was connected to the brine collection system 4 days before the reduction of heating. Although less brine was reported at Borehole 1, some brine was likely lost to condensation

(a) heating period only

(b) heating and cooling periods

Figure 4.19. Asse Brine Migration test brine inflow results (Rothfuchs et al., 1988)

on mechanical parts (Rothfuchs et al., 1988, §6). Nothing was observed during the first 4 days after the heaters were stopped (heater power was reduced gradually over a month), then more began to flow, which continued for up to a month.

Acoustic emission events were recorded during the cool-down phase using a seismometer array installed on the drift floor. There were equipment failures and significant noise problems, but the reduced results show a increase in acoustic emissions as the salt cooled, despite the stepped heater power reduction (Figure 4.20(a)). Acoustic emission source locations were estimated during the end of heating and cooling. A cross section is shown in Figure 4.20(b). Microcracks appear to be disseminated throughout the rock, not only proximal to the heaters.

Post-test core samples, taken around the heaters showed lower average total water content (0.13 wt-%) near the heaters, compared to pre-test samples (0.25 wt-%). Adsorbed pore water content measurements did not show a similar decline (Rothfuchs et al., 1988, Table 7-2). A saturation front was observed approximately 12 cm beyond the central borehole wall.

Good quality data were collected during the Asse heated brine migration tests. Acoustic emission data were novel at the field scale (confirming what was previously only seen in the laboratory), but the instruments suffered from problems, and required significant processing to remove noise. Much less brine was collected during the tests, than was predicted in pre-test modeling efforts. Most brine was collected during the extended heating step-down phase, which was also unex-

Figure 4.20. Asse Brine Migration test reduced acoustic emissions through time and space during cool-down period (Rothfuchs et al., 1988)

pected. Despite the month-long gradual cool-down process, microcracking was apparently still significant – creating observable acoustic emissions and leading to most of the brine release.

BAMBUS II and ADDIGAS isothermal brine injection tests

In the AHE drift at the Asse II facility, isothermal brine injection tests were performed in the very shallow excavation disturbed zone, in conjunction with gas permeability tests. The near-drift testing system involved grouting a 1.8-m plastic sheet to the drift floor, and drilling a small-diameter hydrologic and geophysical sensor borehole array through the middle 1-m section of the sheet. Gas permeability measurements were made very near the surface (10.6 cm depth) to characterize EDZ permeability without borehole leaking problems, which often occur under such limited confinement (see AHE data in Figure C.7 of Appendix C).

Electrical resistivity measurements were made during brine injection episodes as part of BAMBUS II in 2001. Tomographic resistivity interpretation indicated the brine stayed in the top 30 cm of salt. This same experiment was repeated three times during 2004–2007 as part of the ADDIGAS project (Jockwer and Wieczorek, 2008), showing similar horizontal brine flow preference (Figure 4.21).

The salt resistivity testing during brine injection revealed a high anisotropy to brine flow. Brine was injected into both very shallow (10 cm below surface) and slightly deeper (24–40 cm below surface in Figure 4.21) with similar results. Both anisotropy and the depth-graded hydraulic proper-

Figure 4.21. Estimated resistivity tomogram following second ADDIGAS brine injection event. Adapted from Jockwer and Wieczorek (2008).

ties (porosity and permeability) could lead to this response. Since dilation-induced microfractures would preferentially be oriented parallel to the drift face, the salt permeability in the DRZ would be expected to also be anisotropic (Jockwer and Wieczorek, 2008, p. 32).

Laboratory Tests of Brine Effects on Salt Creep

Urai et al. (1986) presented creep test results on dry and brine-bearing salt samples, showing wet samples to be much weaker, especially at very low strain rates ($< 10^{-7} \text{ s}^{-1}$). Low strain rates were considered comparable to those observed in natural environments, as opposed to rapid strain rates commonly used in laboratory triaxial tests. The weaker behavior is associated with solution-precipitation creep associated with recrystallization. Including this effect in models would require a brine-dependent term in the creep constitutive model.

RE/SPEC conducted six triaxial creep laboratory experiments at a range of confining pressures (0.5–15 MPa) (Brodsky, 1990; Brodsky and Munson, 1991). After 8 days of creeping at a constant differential stress, saturated brine was introduced into the sample. The increase in the observed strain rate was largest for the lowest confining pressures. These effects could be explained by considering the rock-water system poroelastic response, rather than ignoring pore pressure effects.

Observations from Brine Related Salt Testing

The following observations are drawn from the brine migration experiments discussed in this chapter.

1. Temperature-related effects

- Avery Island domal salt produced small amounts of **brine inflow under isothermal conditions** (Site AB (Krause, 1983)), but no brine flowed before heating during the Asse test (Coyle et al., 1987). The bedded salt at WIPP and the MCC potash mine flowed significant brine under isothermal conditions (Ewing, 1981b; Nowak, 1986a). Nearly constant brine inflow to boreholes was observed at WIPP for more than 3 years as part of the small-scale brine inflow test (Finley et al., 1992).
- **Higher borehole temperatures** are associated with higher brine inflow rates (e.g., WIPP Room A1 vs Room B (Nowak and McTigue, 1987), 1-kg test (Hohlfelder and Hadley, 1979), Salt Block II (Hohlfelder, 1980), Project Salt Vault (Bradshaw and McClain, 1971) and the three borehole MCC test (Shefelbine, 1982)).
- Most brine (but probably not all brine-inclusion moisture) is transferred from the intra-granular porosity to the intergranular porosity when salt is **heated to the decrepitation point** (e.g., the salt cracker test (Hohlfelder et al., 1981), pre Salt Vault borehole heater tests in Hutchinson KS (Morgan, 1963), and MCC in situ test (Ewing, 1981b)). The decrepitation point depends on the composition of the evaporite, and has been observed to vary between different sized inclusions (Wilcox, 1968). Appendix A discusses laboratory brine characterization tests, which included decrepitation observations.
- **Acoustic emissions** have been observed during heating, cooling, and decrepitation of salt in the laboratory and field (e.g., salt cracker test (Hohlfelder et al., 1981) and Asse in situ test (Rothfuchs et al., 1988)). In the laboratory, they are closely correlated with increased brine inflow (salt cracker test) and salt dilation in triaxial tests (see Figure C.1). They are more difficult to measure accurately during in situ tests due to noise (Rothfuchs et al., 1988).
- Microfracturing due to high **cool-down tensile stress** can still release significant brine, even after damage has occurred due to decrepitation, rupturing brine inclusions and damaging salt crystal structure (e.g., salt cracker test (Hohlfelder et al., 1981)). A significant portion of overall brine volume collected is often released during cool-down phases related to heater shut-down at both the laboratory and field scales (e.g., Salt Vault (Bradshaw and McClain, 1971), Salt Block II (Hohlfelder, 1980), salt cracker test (Hohlfelder et al., 1981), Asse in situ test (Rothfuchs et al., 1988), and MCC potash mine single- and three-heater tests (Ewing, 1981b; Shefelbine, 1982)).
- Salt **gas permeability reduces during heating** (Avery Island heater Site C, Figure 4.4(b) and Blankenship and Stickney (1983)), even as brine inflow rates remain largely constant during heating (Figure 4.3(a) and Krause (1983)). This suggests temporal permeability reduction near the borehole due to heating happens quickly, associated with

the initial brine pulse observed at the beginning of tests (e.g., see A1041 and A1042 in Figure 4.13), before steady-state brine inflow behavior begins (see Appendix C for more on brine and gas permeability testing).

2. Heterogeneity

- **Clay, shale, or anhydrite layers** in salt result in much higher brine inflow rates (e.g., WIPP Rooms A1 & B (Nowak and McTigue, 1987) and Salt Vault Room 5 (Bradshaw and McClain, 1971)). Clay gives off bound water at relatively low temperatures (100–150° C), non-salt components have much higher permeabilities than clean halite, and they have different mechanical responses compared to halite (no creep closure of pores and microfractures during heating). Anhydrite layer MB139 at WIPP is known to be highly fractured, leading to increase brine flow (Deal et al., 1995, Appendix E).
 - In both boreholes and rooms, **brine flows in at isolated locations** under both isothermal and heated conditions, rather than uniformly across excavated surfaces (Shefelbine, 1982; Deal et al., 1995). During heating, salt encrustations are observed to form along grain boundaries in quick bursts, rather than growing steadily with time (e.g., MCC potash mine three-heater test (Shefelbine, 1982)). This discontinuous behavior in both space and time reflects a lower limit to the porous medium approximation used to describe flow in salt, related to salt crystal or grain size.
 - **Borehole directionality.** Vertical boreholes often flow brine isothermally for years, while horizontal boreholes and seeps in rooms dry up more quickly (Deal et al., 1993, 1995). Early Project Salt Vault tests showed much more brine inflow to heated vertical boreholes, compared to similarly heated horizontal boreholes (Morgan, 1963). Vertical boreholes cross more geologic layers, providing more opportunities for higher-permeability clay and anhydrite layers to provide saturated pathways to the borehole. Some vertical boreholes at WIPP have flowed isothermally for many years (Finley et al., 1992).
3. **Vapor transport models** do not predict brine inflow correctly at early times after a change in heater power (Hadley and Faris, 1981; Shefelbine, 1982). In WIPP Room A1 boreholes there was a 4× change in brine vapor pressure, but no significant change in brine inflow (Nowak, 1986a; Nowak and McTigue, 1987). Tests were designed at Asse to provide evidence on the significance of vapor transport, through the use of pressurized boreholes (Westinghouse Electric Corporation, 1983b). Unfortunately, an unknown amount of brine was lost to condensation in the sealed borehole (site 1), which resulted in low total inflow totals there and inconclusive results (Rothfuchs et al., 1988).
 4. **Gas vs. brine permeability.** Gas permeability is useful for delineating excavation damage and dilation, as was done in tests at Avery Island, but under most conditions gas typically does not displace brine (i.e., two-phase viscous fingering flow). Appendix C discusses details associated with both brine and gas permeability testing in salt.
 5. **Radiation effects.** Bradshaw and McClain (1971) hypothesized radiation may work-harden salt, leading to increases in brine releases. Differences in inflow rates between Sites 2 and 4 at the Asse brine migration test (Rothfuchs et al., 1988) may also be due to this proposed

effect. Reynolds and Gloyna (1960) performed tests showing irradiation does not appreciably change mechanical salt properties (i.e., Young's modulus and Poisson's ratio), but it may increase creep rates.

6. **Water content.** Domal salt typically has approximately an order of magnitude less water content than bedded salt (0.001–0.02 wt-%), does not have significant brine inclusions or appreciable decrepitation response (Bradshaw and McClain, 1971), and in general releases much less brine during heating (e.g., Avery Island (Krause, 1983) and Asse (Rothfuchs et al., 1988)). Water content of Permian bedded salt (WIPP, MCC potash mine, Palo Duro Basin, Lyons & Hutchinson, KS) is typically in the range 0.4–0.6 wt-%, with some much higher values possible (see Appendix A). Intergranular porosities of reconsolidated WIPP salt are only 0.1–0.2 vol-%, based on laboratory hydrostatic loading tests (Stormont and Daemen, 1992).

Chapter 5

Summary and Recommendations

We have synthesized the theory governing the relevant physical brine flow processes and mechanisms in geologic salt. We summarized both previous and current numerical and analytical modeling efforts, as well as laboratory and in situ testing relevant to both prediction of brine migration to a heated borehole in salt and estimation of relevant material properties. Based upon observations from previous testing, and conclusions from the development of the governing equations, we describe a chronology of important physical processes impacting brine inflow to heated and unheated excavations.

Salt Hydraulic Behavior Near an Isothermal Excavation

Appendix B includes discussion and examples related to the disturbed rock zone (DRZ) or excavation damaged zone (EDZ). Before any excavation occurs, the steady-state flow system is typically saturated with brine at static formation pressure near lithostatic pressure (e.g., ≈ 15 MPa at WIPP), and intergranular porosity is low (e.g., 0.1–0.2 vol-%). In pure halite an interconnected intergranular porosity or measurable permeability may not exist; only an intracrystalline porosity consisting of brine inclusion may be present. The salt stress state is isotropic, with no deviatoric stress and therefore no creep.

Once excavation occurs, rock damage and disturbance begins to occur. An excavation disturbed zone (EdZ) immediately extends far away from the excavation face, and is characterized by reduced pore pressure and an altered stress field. This is driven by stress changes due to the excavation, which enforces the atmospheric pressure boundary condition at the opening. The EDZ extends a shorter distance into the rock, characterized by large deviatoric stresses, leading to salt dilatation. Dilatation includes opening of existing apertures and creation of new micro- and macro-fractures, preferentially oriented parallel to the excavation (e.g., up to 3 vol-%). The mechanical increase of porosity and fracture aperture leads to increased intrinsic formation permeability and decreased air-entry pressure. Even without brine flow, relative saturation decreases due to the increased void volume, which leads to a sharp decrease in *relative* salt permeability to brine. Salt begins to creep due to deviatoric stress.

After excavation, the salt is no longer a saturated system at mechanical and hydraulic steady state. The salt porosity is highest at the excavation away from corners and reduces to its undis-

turbed value approximately one excavation radius deep into the formation (for WIPP-like conditions). Preferential fracture orientation also leads to anisotropic intrinsic formation permeability, enhancing brine flow parallel to the excavation surface. A saturation front has moved into the salt, due decreased air-entry pressure.

During this early-time EDZ development, brine redistributes under variably saturated conditions. A material boundary marks the saturated zone edge, separating brine-filled from nearly air-filled pores. Steep material property gradients have been imposed upon the system. Some brine will flow to the excavation, driven by pressure gradients. Most brine flowing towards the cavity fills the halo of newly created porosity surrounding the cavity, and does not discharge immediately to the excavation. Salt creep is slowly working to close this porosity, faster in brine-saturated salt than in dry salt. Significant air flow may occur in a ventilated mine, but air flow through the unsaturated portions of the salt and macrofractures parallel to the wall are expected to be minimal. If ventilation air humidity is low, some evaporation may occur, but this is also expected to be minimal.

Clay or anhydrite layers also experience dilation. Their intrinsic permeabilities and porosities are several orders of magnitude higher than salt. Some sliding or shearing occurs at the interface between salt and non-salt layers. Non-salt layers do not experience creep closure of newly opened porosity. The multi-phase moisture release curve for clays is very different from coarse granular material, with a much higher air entry pressure. Clays remain saturated under the pressure conditions which desaturate pure salt.

Vertical boreholes typically cross several geologic layers, and have a smaller more uniform EDZ due to their smaller diameter and circular cross section. If clay layers intersect boreholes, they typically provide a saturated pathway from the far field to the borehole wall. Horizontal boreholes are more like excavated rooms, typically remaining in a single geologic layer, depending on the local geology. Vertical boreholes often flow brine under isothermal conditions for long time periods, while horizontal boreholes do not.

Heat Effects on Hydraulic Salt Evolution

Heating the EDZ will reverse some damage effects described in the previous section. Immediately upon heating or an increase in temperature, the brine and salt grains will expand. This expansion reduces microcrack apertures associated with intergranular porosity. Due to weakening of the salt, large-scale cracks will often increase in size, accelerating collapse or failure of mined openings. Two factors contribute to the expulsion of brine from the salt upon heating:

1. Since initial excavation, but before heating, additional brine has flowed into the expanded halo of porosity around the excavation from the far field, which will be expelled if heating manages to reduce porosity to near pre-excavation levels.
2. Entrapped air will likely occupy some of the reduced porosity near the excavation, since

thermal expansion is strongest near the heaters. This potentially seals off the pathway air used to enter the salt during borehole drilling.

By reducing the porosity and fracture aperture, the intrinsic formation permeability decreases. Competing with this process, the increase in relative saturation due to aperture closure increases the *relative* brine permeability. The increase in saturation leads to more saturated pathways to the excavation surface.

Temperatures above 250° C are often associated with brine inclusion decrepitation in bedded salt. Exact decrepitation temperatures are dependent on the size and composition of brine inclusions and the salt stress state. Decrepitation leads to a large brine release, since brine inclusions are often a large component of total water content in bedded salt deposits. Damage due to decrepitation releases brine due to fracturing individual salt grains, and may increase intergranular porosity, but may not increase the intergranular permeability significantly.

Higher temperatures also accelerate creep closure of dilation-induced damage in salt, which help to reduce deviatoric stresses.

Cooling of salt produces new microfractures between and potentially through salt grains due to tensile salt failure as salt grains contract. Microfracturing releases stress energy and increases bulk salt permeability near the borehole, enhancing convergent intergranular brine flow toward the borehole. Microcracking and permeability increases happen quickly, while saturation reduction may occur more slowly, leading to the observed spike in brine inflow soon after the peak of heating. To avoid this often significant brine release, the cooling rate must be low enough to allow salt creep to dissipate tensile stress due to thermal contraction.

Proposed Experiments and Tests

Based upon the testing review in Chapter 4, the following proposed tests could be used to fill current knowledge and data gaps:

1. Conduct a core-scale laboratory test like the salt cracker experiment (Hohlfelder et al., 1981), where a bedded salt sample is heated past the decrepitation point ($\geq 250^\circ \text{C}$), while monitoring temperature, brine outflow, and acoustic emissions. The test could be performed in a triaxial test device, where different axial and confining stresses can be applied (e.g., Schulze et al. (2001)). The sample's gas permeability should be estimated as the test proceeds, (e.g., Sutherland and Cave (1980)).

This test would explore the effects that confining stress has on brine inclusion decrepitation, and the effects decrepitation has on bulk salt permeability and porosity (currently unknown). These results could be used to justify an increase to the customary limit of 200° C used in salt repository design. This limit was proposed for the purposes of avoiding decrepitation, based upon decrepitation temperatures observed in the laboratory. Effects of confinement

may increase in situ decrepitation temperatures, allowing us to safely design repositories for higher temperatures.

2. Conduct a core-scale laboratory gas or brine permeability test on a sample in a heated triaxial apparatus. Measure acoustic emissions and permeability through time during cooling. Test the effect different cooling rates or temperature jumps have on salt properties, under different confining pressures.

It has been postulated that issues observed during cooling in laboratory and in situ experiments would not affect actual waste emplacement, where radioactive decay rates lead to very gradual temperature declines. Increases in acoustic emissions and permeability have been observed at Avery Island, which reduced heating over approximately a week, and at Asse (Rothfuchs et al., 1988), where heating was reduced from the maximum temperature over the course of a month.

3. Core-scale laboratory tests to estimate multi-phase flow properties of halite, anhydrite, and clay samples from bedded salt formations.

This test would estimate air-entry pressure and pressure-saturation data for relevant evaporites, ideally at several confining pressures representing different amounts of salt damage. Little is known about the exact nature of multi-phase flow in salt, especially how the moisture-redistribution properties respond to changes in temperature and stress. These parameters are necessary to accurately parametrize multi-phase flow models.

4. An in situ heated brine inflow test in bedded salt using more sensitive microseismic data acquisition equipment (e.g., Westinghouse Electric Corporation (1983b); Rothfuchs et al. (1988)), with gas permeability tests (e.g., Krause (1983)). Microseismic and gas permeability data should be collected in boreholes surrounding the central heater borehole before, during, and after heating.

This test would measure the temporal and spatial distribution of stress-induced damage and how this relates to salt gas permeability. The test could also be conducted in multiple boreholes at several cooling rates. High temperatures could induce decrepitation conditions, which could be monitored through permeability and acoustic emissions observations.

5. Laboratory- and borehole-scale geophysical tests for salt and brine characterization:

- (a) Nuclear magnetic resonance methods can potentially be used to estimate the fraction of brine in intergranular, intragranular, and hydrous minerals.
- (b) Various electromagnetic (EM) surveys (e.g., resistivity, induced polarization, time-domain EM, ground-penetrating radar, and streaming potentials) can be used to economically characterize different EDZ aspects, both spatially and temporally. Salt resistivity is relatively well known as a function of brine content.

Some methods used historically to characterize geology or the excavation disturbed zone (Borns, 1997; Holcomb et al., 2002) may warrant additional tests, due to advances in sensor and signal-processing technology. The results of many geophysical methods could be improved by interpreting results of multiple different geophysical surveys simultaneously or by

making temporal observations during processes of interest (e.g., heating, cooling, or brine injection).

6. Any heater tests should continue to monitor for brine flow for at least a week after heating has stopped, and preferably until brine inflow has reduced to near-isothermal conditions. This has been observed to take from two weeks at Salt Vault (Bradshaw and McClain, 1971), to as long as a month at Asse (Rothfuchs et al., 1988). Although it is conjectured this cool-down brine pulse will not occur under repository conditions, it is an essential part of the salt behavior, which we should strive to understand and quantify with our coupled models.

Conclusions

We have outlined the governing equations for brine flow through intact salt, especially considering the effects of heaters in boreholes. The system is generally the coupled thermoporoelasticity problem (thermal, hydraulic, and mechanical processes). In general the thermal-hydraulic-mechanical problems is also coupled to dissolution or other chemical reactions (not considered here). Because of the property-dependence of many constitutive models and parameters, we must commonly resort to numerical simulation with non-linear iteration.

Although several large-scale field and laboratory tests have been conducted, little is still known about the details of salt decrepitation, cooling microfracture, and multi-phase flow in salt and associated evaporites. Well-designed and targeted tests can be performed to increase confidence and close some identified knowledge and data gaps.

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Appendix A

Salt Water Content

In this appendix, we cite laboratory studies performed to estimate both the total brine content, and its distribution in bedded geologic salt. Before we can quantify the duration and amount of brine inflow to an excavation or borehole in salt, we must understand the available brine sources in geologic salt. Roedder and Bassett (1981) and Gevantman (1981) provide summary tables of geologic salt water content values reported in the literature. Roedder and Bassett (1981) proposed a methodology for estimating brine content accurately, and include a table of brine content estimates for a wide range of salts from the literature. They separated water found in salt into internal and external waters. External water can be attributed to saturating the rock over geologic time scales (i.e., pore water in salts and clays under the water table). Internal water is instead incorporated into the crystal structure of minerals in the rock (i.e., brine inclusions and water of hydration).

Most studies have focused on thermogravimetric analysis (TGA) used to characterizing brine inclusions and various hydrated minerals. Typically, the intergranular brine content is estimated as the difference between total water content and water content attributed to intracrystalline water, or through hydrostatic reconsolidation tests.

Stormont and Daemen (1992) determined salt core porosity in laboratory tests exposed to hydrostatic mechanical loading. Initial porosities were high and quite variable (0.4–1.6 vol-%), indicating dilation and damage due to the process of removing and handling the core. After hydrostatic loading, residual porosity was calculated to be 0.1–0.2 vol-%, representative of bedded salt intergranular porosity.

Brine inclusions move slowly under an applied thermal gradient or rapidly during decrepitation. Wilcox (1968) indicated heating crystals to the decrepitation point associated with large brine inclusions does not always rupture smaller inclusions in the same salt. Roedder and Belkin (1980) performed brine migration studies on ERDA-9 core where fluid inclusions were found near crystal boundaries. Samples were heated to 150° C for as long as 1000 hours to observe fluid inclusion behavior at grain boundaries. Inclusions lost 50–90 vol-% of fluid at boundaries to intergranular pore water. The remaining brine inclusions began moving back down the thermal gradient.

The release of bound water in hydrated minerals is associated with different volatilization temperatures for each mineral type (Kitagawa, 1972; Roedder and Bassett, 1981). Some water given off at room temperature is due to brine evaporation near the surface of intact samples, or can be attributed to recently ruptured brine inclusions in crushed samples.

Gravimetric methods report brine content as a weight percent (wt-%), while mechanical and geophysical methods estimate volume percent (vol-%) brine content. Assuming pure halite and NaCl-saturated brine, divide by 1.71 to approximately convert from volume-% to weight-% (e.g., 0.5 vol-% brine is 0.29 wt-% brine for pure salt).

A.1 Salt Vault Decrepitation Laboratory Tests

Bradshaw and McClain (1971, §2.2) summarized studies before Project Salt Vault involving over 50 heated run-of-mine salt samples from different bedded or domal salt sources. Most bedded salts exhibited shattering or severe fracturing (decrepitation) in the range 240°–320°C, with two samples of one bedded Ohio salt (Fairport Harbor) fracturing at 380° C, and two samples from a bedded New York salt (Retsof) decrepitating in the range 400°–625° C. The bedded Retsof salt sample with the very high decrepitation temperature was found to have a low water content – about 0.06 vol-% (Bradshaw and McClain, 1971, §11.2.4.3). Domal salt samples never exhibited this shattering behavior up to 625° C (no brine inclusions were observed in domal salt samples).

Salt samples from the Hutchinson Carey salt mine were brought to decrepitation in the range 260–320° C using irradiation with a dose of 5×10^8 R or greater. This experiment showed large radiation doses do not appreciably change the decrepitation salt temperature; radiolysis does not produce significant vapor pressure in brine inclusions to enhance rupturing.

Bedded salt from the Hutchinson Carey mine averaged 0.4 vol-%, while salt from the Lyons Carey mine (where Salt Vault heater tests were conducted) only averaged 0.2 vol-%, but was highly variable. Brine content in post-test samples surrounding the Salt Vault heaters had average water content in the range 0.3–0.5 vol-%.

A.2 MCC Potash Mine Laboratory Tests

Hohlfelder (1979b) analyzed the volatile content of nine salt samples from MCC potash mine heated in 25° steps from 200° to 425° C. Results indicate approximately 0.5% mass lost, attributable to water content. The water content was largely attributed to 10–20% polyhalite content in the rocks.

Hohlfelder and McMurtry (1983) performed follow-up TGA of evaporite samples from the MCC potash mine up to 370° C to determine water content. The initial mass loss ($\approx 0.25\%$ at room temperature) occurred during the crushing of the sample (Figure A.1), and was believed to represent brine trapped in brine inclusions. The second jump in mass loss was associated with the polyhalite dehydration. Roedder and Bassett (1981) consider this polyhalite water volatilization temperature to be low, possibly due to impurities.

Figure A.1. Average mass loss for 12 MCC potash mine salt samples during heating (Hohlfelder and McMurtry, 1983)

A.3 WIPP Thermogravimetric Analysis

Powers et al. (1978) analyzed Salado Formation cores from WIPP boreholes AEC-7, AEC-8, and ERDA-9. They mostly performed petrographic, thermogravimetric, and crushing analysis on small samples.

Their results included computing mass loss analysis during sample heating up to 500° C. The mass loss was attributed to water loss from hydrated minerals and clastic interbeds. Figure A.2 shows characteristic results from ERDA-9 for the main salt types encountered. Relatively pure rock salt (A) was observed to incur limited mass loss to temperatures as high as 500° C, due to low total water content. A significant mass-loss occurs above 300° C for polyhalite-bearing salt (B), and a smaller mass-loss occurs at approximately 100° C for argillaceous salt (C).

Westinghouse Electric Corporation (1983a, §10) tested 26 evaporite samples from the WIPP underground using TGA. The samples were pulverized first, releasing most intragranular water at room temperature without decrepitation. One crushed sample decrepitated below 250° C, five crushed samples decrepitated in the range 250°–400° C, and four crushed samples decrepitated in the range 400°–600° C (therefore 18 crushed samples did not decrepitate below 600° C). Two samples were noted to dehydrate clays in the 25°–150° C interval (smectite and illite). In the 250°–400° C interval, dehydration of polyhalite was common. In the hottest interval (400°–600° C) hydroxyl groups were removed from clays (kaolinite and smectite). An estimate of maximum total water content was 1.8 wt-%, with a mean of 0.59 wt-%. This range was considered likely to be an over-estimate, because a multiplication factor from Hohlfelder and McMurtry (1983) was used to estimate the fraction of water mass lost during the initial crushing at room temperature.

Figure A.2. Characteristic total mass loss curves from different Salado Formation salt types in ERDA-9 core (Powers et al., 1978)

A.4 Palo Duro Basin Salt Laboratory Tests

Owen and Schwendiman (1987) performed laboratory tests on 43 bedded Permian salt cores from the Palo Duro Basin. Tests were performed to determine the water content, the distribution of different water forms (free water in pores, fluid inclusions and bound water in hydrated minerals), and the decrepitation temperature, which they called “point of thermal fracture”.

All but 2 samples decrepitated in the range 250–350°C, with the most common temperature being 325° C. The two samples that did not decrepitate during the tests also had the highest percentage of insoluble non-salt content (around 30%). The samples had water contents ranging from 0.17 to 5.53 wt-%, with a median water content of 0.48 wt-%.

Appendix B

Disturbed Rock Zone Development

In this appendix, we discuss the disturbed rock zone (DRZ). Although this discussion does not directly relate to brine flow in salt, it is important because without the DRZ, brine flow in salt would be insignificantly small. We outline the geomechanical basis and evolution of the DRZ, observations from a small-scale salt petrofabric study that support observations from larger-scale brine permeability tests, and model-predicted geometry effects of square and rectangular excavations.

The existence and development of the DRZ or the excavation damaged/disturbed zone (EDZ/EdZ) are well known and documented (Gramberg and Roest, 1984; Borns and Stormont, 1988; Stormont, 1990b; Droste et al., 1999; Holcomb et al., 2002; Hansen, 2003; Davies and Bernier, 2005; Tsang et al., 2005). Two damaged regions can be identified in rock excavations (not specific to salt) (Davies and Bernier, 2005):

EDZ The “Excavation Damaged Zone” is the dilatant region close to the opening, where volume and porosity increases occur. It is characterized by fracturing and permeability increases of several orders of magnitude over intact salt rock (e.g., see the WIPP small-scale mine-by experiment (Stormont et al., 1991b), BAMBUS II (Bechthold et al., 2004, §4), and ADDIGAS (Jockwer and Wieczorek, 2008)).

EdZ The “Excavation disturbed Zone” reaches further into the rock, including the region where the stress field and brine pore pressure are disturbed by the excavation (e.g., Beauheim and Roberts (2002) and Figure 4.18). The EdZ outside the EDZ shows no change in hydraulic properties.

Both zones’ extents are controlled by the rock strength properties (i.e., Young’s elastic modulus and Poisson’s ratio) and lithostatic stress at a given site. Figure B.1 shows the plastic deformation zone extends approximately one excavation radius into the salt for 2000 ft of overburden. Greater depths result in a larger EDZ, but less stress concentration at the excavation.

B.1 Pre-excavation State

Before room excavation, an isotropic stress state exists ($\sigma_1 = \sigma_3 = p$), where the maximum and minimum stresses are approximately equal. The principal stresses are also equal to the pore

Figure B.1. Analytical solution for stress state around a cylindrical opening, accounting for creep (plastic region boundary at cusp in σ_t curves) and excavation depth (Serata and Gloyna, 1959)

pressure and lithostatic load (the weight of the rocks above the excavation interval). Salt cannot withstand deviatoric stresses for long time periods, due to the slow, but equalizing effects of creep. Pore pressures are roughly equal to confining pressures due to the very low brine permeability of undisturbed salt. Intact salt lacks an extensive connected intergranular porosity, which would normally be the mechanism for pore pressures re-distribution (i.e. the system is very near the ideal “undrained” limit used as an end-member in poroelastic analysis).

B.2 Response of Salt to Excavation

Immediately upon excavation, a large deviatoric stress exists ($\sigma_3 \approx 0$ adjacent to the excavation), which drives the salt deformation. Elastic deformation occurs nearly instantaneously in response to the excavation. There are two forms of time-dependent inelastic deformation which follow (Hansen, 2003, §4.1). Viscoplastic flow is driven by the deviatoric stress state, independent of the average stress. This creep type does not induce damage in the rock salt. Damage-induced flow occurs when the deviatoric stress is large compared to the average stress. This mechanism accumulates microcrack damage in the salt through time. Finally, microfracture healing (i.e., damage recovery) occurs in the salt when the deviatoric stress becomes small compared to the average stress. The extent and aperture of salt macrofractures may grow and eventually lead to salt failure (Figure B.2). Bechtel National (1986) performed detailed macrofractures mapping at WIPP, including their relationship to bedded geology, as exposed in drifts and large-diameter boreholes.

The temporal re-development of the EDZ in the floor of a 20-year old excavation was explored

Figure B.2. Cartoon of observed damage surrounding a typical WIPP disposal room (Borns and Stormont, 1988)

in the ADDIGAS tests, which are discussed in Appendix C (Figure C.7). Although the EDZ develops quickly during initial excavations, subsequent re-development may take several months.

B.3 Petrofabric DRZ Investigation

In the EDZ, dilation leads to porosity and fracture aperture increase, which in turn leads to increases in permeability and air-entry pressure. An EDZ petrofabric investigation was conducted on Asse and WIPP salt core, as part of BAMBUS II (Bechthold et al., 2004, §4.3). Estimates of salt porosity and fracture aperture as functions of distance from the excavation were made from microscopically analyzed samples (Figure B.3). These results show trends of decreasing porosity and fracture aperture with depth into the borehole for both domal and bedded salt. Based on major fracture orientation in the WIPP core with respect to the rib, the authors had confidence the observed fractures and porosity were representative of in situ conditions (Bryan et al., 2003).

Although the coring and handling process associated with laboratory samples increases both porosity and fracture aperture, it is believed this increase is uniform in the samples and “over-printed” on the variable dilatancy distribution associated with the primary excavation. Relative changes in porosity and fracture aperture should reflect in situ conditions, even if the absolute values do not.

B.4 Excavation Shape Effects

The damaged zone surrounding a rectangular excavation is asymmetric, with stress concentration occurring near the corners (Figures B.2 and B.4). Deviatoric stresses (difference between

Figure B.3. Salt petrofabric study results for WIPP and Asse salt, showing variation in hydraulic properties with distance from excavation face (Bechthold et al., 2004).

maximum and minimum principle stresses) are greatest in the middle of the sides of the opening, leading to the largest amount of dilation and damage.

Figure B.4. Representation of fractures observed around mined openings at Asse (Borns and Stormont (1988), after Gramberg and Roest (1984, Fig. 8))

When unsaturated, both microscopic and macroscopic fractures behave as barriers to brine flow. Macroscopic vertical rib and en echelon fractures in the back and floor may never become filled with brine, and therefore effectively isolate salt near the excavation from the saturated salt

Figure B.5. En echelon fractures in the back at WIPP (Hansen, 2003)

mass in the far field (see examples in Figure B.5). This is in agreement with BSEP observations (Chapter 4), which saw short-lived brine weeps on the ribs of underground rooms. Boreholes provide access directly to brine-saturated salt beyond the macroscopic air-filled fractures surrounding the excavation.

Near-excavation fractures in the excavation sides (ribs) tend to be vertical, while fractures above and below the excavation tend to be sub-horizontal, including en echelon fractures illustrated below the excavation floor in Figure B.2. Fractures tend to follow an elliptical shape deeper into the intact formation (Figure B.4).

Structural modeling of dilation and damage around rectangular excavations show similar distributions of predicted dilation (corresponding to an increased porosity) and rock damage (compare Figures 4.17 and B.6). Models predicted less dilation at the room corners than was observed (compare Figure C.4 with Figure B.6). Despite this, the general agreement between modeled damage and observed gas flowrate distribution illustrates the main process that increases gas flowrate is dilation, which is included in the models.

Figure B.6. Model-predicted damage surrounding a typical WIPP disposal room including effects of clay and anhydrite layers (Van Sambeek et al., 1993)

B.5 WIPP Hydraulic Fracturing Tests

Hydraulic fracturing tests are used to assess the in situ stress state in salt. They were conducted at WIPP in halite (December 1983 and February 1986) and anhydrite marker beds MB139 and MB140 (November 1991 to March 1994) below the repository disposal horizon. Early stress-verification tests were conducted in Room G at WIPP, which consisted of hydraulic fracture tests performed at different distances along a horizontal borehole, which proceeded drift mining. The first 10.2 cm diameter borehole was drilled 125 m deep into the Room G access drift. Fluorescent dye was added to the hydraulic fluid to allow mapping the fracture pattern with a black-light source after the drift was excavated Figure B.7. Examination of the major fracture orientation at the face of the excavation indicates the minor principal stress plane (Wawersik and Stone, 1985; Wawersik, 1988).

A marker bed hydraulic fracturing experiment was conducted to address the gas generation consequences in disposal rooms in the Salado formation, and specifically, experimental evaluations of analysis concerning the gas pressurization of anhydrite interbeds such as MB139 (Davies, 1991; Wawersik et al., 1997). To accomplish this, complementary hydraulic fracturing and hydrologic tests were conducted in MB139 and MB140. Considerable variability was recorded in the measured formation pore pressures and permeabilities in MB139 located 1-2 m below the repos-

Figure B.7. WIPP Room G fractures observed using blacklight during excavation after hydraulic fracturing with fluorescent dye (Matalucci, 1988).

itory horizon, and to a lesser extent in MB140, 6 m below the the WIPP experimental area floor. The observed variability suggested a strong influence of sub-horizontal networks of preexisting partially and fully healed fractures. It was proposed MB139 is altered by the influence of nearby excavations (Stormont et al., 1987; Stormont, 1990a; Roberts et al., 1999). MB140 served as a virgin analog of MB139 and other anhydrite interbeds in the vicinity of the repository horizon.

The maximum breakdown pressures observed in the deeper MB140 ranged from 22-13 MPa, while they were 19-12 MPa in MB139. Similar to the Room G hydraulic fracturing tests, it was found the vertical principal compressive stress component was smallest. Hydraulically induced fractures were found to propagate horizontally within the marker beds, and relatively large (0.2-0.4 mm) residual openings were created, which were confirmed by orders-of-magnitude increases in permeability.

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Appendix C

Salt Permeability Testing

In this appendix we discuss some generalities regarding lab and in situ brine and gas permeability tests in salt. Salt crystals are impermeable to flow (Gloyna and Reynolds, 1961), and intact salt bulk permeability is very low, therefore it is difficult to measure without specialized field testing equipment and laboratory apparatus. Because salt deforms, creeps, and heals under relevant repository conditions, the permeability from a single experiment is dependent on several relevant conditions of the region or sample being tested, including:

- current stress state (i.e., confining pressure and differential stress);
- temperature;
- salt crystal or grain size;
- stress, strain, and dilation history;
- moisture content and humidity (i.e., saturation);
- pore pressure (i.e., effective stress); and
- impurities in the salt (i.e., clay and anhydrite).

Although brine permeability is arguably the more relevant parameter we are interested in at the repository scale, gas permeability tests are simpler to conduct and tests can be used to reveal the extent of damage in salt due to dilation effects (i.e., the DRZ). Due to the high air-entry pressure which may exist in narrow salt pores, undamaged salt away from mine openings may be essentially impermeable to gas at pressures ≤ 3 MPa (Stormont, 1997b).

When considering single-phase gas flow at low pressures, test interpretation must account for non-linear gas flow (Klinkenberg, 1941). In general, gas permeability will be dependent on gas pressure, with the “true” brine permeability equal to the gas permeability extrapolated to infinite pressure. To account for these effects, tests must be conducted at several gas pressures to extrapolate the results, or more often tests are simply conducted at a single high gas pressure, assuming the resulting gas permeability closely approximates the relevant brine permeability.

In situ gas permeability tests cannot assume the rock is dry (as laboratory tests often can), so multi-phase flow may be occurring. Gas permeability measurements commonly assume gas does

not displace brine. It is assumed gas permeability tests are testing the gas-filled porosity and not changing the brine saturation (Stormont, 1997b), which would result in viscous fingering (Dullien, 1992, §6.3.7). Viscous fingering effects occur when a less-dense nonwetting fluid displaces a denser wetting fluid (i.e., desorption). When interpreting gas permeability tests where gas has displaced brine without accounting for this effect, estimated gas permeabilities will appear to be pressure dependent (Stormont, 1997b).

Brine can easily displace gas in multi-phase flow, if the gas is not trapped. Despite the relative ease with which brine will displace gas, infiltration is a non-linear process, which cannot be accurately interpreted using a single-phase saturated flow model. In situ brine permeability tests are also subject to compressibility and compliance issues due to the combination of the low brine compressibility and the low salt permeability. Accurate in situ brine permeability testing requires very long tests with complex testing equipment and interpretation techniques (Roberts et al., 1999).

Several laboratory brine and gas permeability tests have observed decreasing permeability during tests (Reynolds and Gloyna, 1960; Sutherland and Cave, 1980; Gilpatrick et al., 1982; Baes et al., 1983; Peach et al., 1987). This observed decrease has been attributed to the following proposed mechanisms:

- plugging of very small aperture openings – permeability increases after flow direction change (Reynolds and Gloyna, 1960);
- closure of intergranular porosity through viscoelastic compaction (Isherwood, 1981);
- surface tension drawing brine into initially dry samples (Isherwood, 1981); and
- pressure-solution removal of fracture wall asperities (Baes et al., 1983).

Lai (1971) and Reynolds and Gloyna (1960) found it took approximately 6.5 days to reach a minimum steady-state apparent permeability value. Tests using kerosene and helium always resulted in higher estimated permeabilities than brine, for the same samples (Reynolds and Gloyna, 1960; Gloyna and Reynolds, 1961).

C.1 Laboratory Permeability Testing

Sutherland and Cave (1980) and later Stormont and Daemen (1992) performed laboratory permeability tests on WIPP salt cores, observing gas permeability to be a function of confining pressure. German salt-repository research programs have resulted in several laboratory studies on salt core permeability during deformation and healing (e.g., Schulze et al. (2001); Popp et al. (2001); Wieczorek et al. (2010)). These studies have furthered the development of numerous constitutive models for salt deformation.

In triaxial tests, a large stress is applied axial to a cylindrical sample, with a lower confinement level along the sample sides. During the early compaction phases (region I in Figure C.1), the sample re-consolidates (negative volume strain and increasing seismic wave velocity). In the second

Figure C.1. Schematic illustrating physical property changes during typical salt core deformation (Schulze et al., 2001)

phase microcracking begins to occur (observed as acoustic emissions and decreasing seismic wave velocities), due to growing differential stress, leading to a sharp increase in sample permeability. Further deformation leads to more volume strain and a slight increase in sample permeability.

Before excavation of an underground room in salt, the salt is initially in an isotropic stress state. Excavating the salt quickly creates a large deviatoric stress and large volume strain (dilation), which results in increased porosity and permeability (Figure C.2, analogous to region II in Figure C.1).

C.2 WIPP Gas Permeability Experiments

Stormont (1997b,a) summarized the numerous in situ gas permeability tests at WIPP, including results of the small-scale mine-by experiment (Stormont et al., 1991a). The small-scale mine-by experiment measured gas and brine permeability in 4.8-cm diameter boreholes over a 65-cm interval 8-m deep into the floor before, during, and after excavation of a 96.6-cm diameter central borehole.

A damaged zone was found to propagate into the salt almost immediately upon excavating the large-diameter borehole, with larger effects observed in brine-filled boreholes compared to

Figure C.2. Gas permeabilities of Asse cores taken from different depths (Peach et al., 1987)

gas-filled boreholes. A pressure diffusion equation provided moderate quality fits to the observed buildup data before mining began. Ranges of permeability and porosities were estimated, which bracketed observed data. A small pressure buildup was observed during coring the large-diameter borehole. A close observation point (10 cm beyond the edge of the large borehole) included a temperature time series, which indicated a 5° C rise associated with drilling the nearby borehole. The pressure rise was attributable to frictional heating from drilling, which led to differential thermal expansion of the halite and brine.

The small-scale mine-by test resulted in an good dataset, which illustrated temporal changes in both brine and gas permeability measurements, due to a controlled excavation. The test delineated the presence of a saturation front surrounding the large borehole approximately $2R/3$ deep into the formation (Figure C.3). It was assumed the effects of excavating Room L1 were affecting the results at 8 m depth because static formation pressure was only 3 MPa.

Gas permeability tests were also conducted in numerous borehole intervals emanating from the N1100 drift of the WIPP north experimental area (Borns and Stormont, 1988). The results show a clear increase in gas flowrate near the excavation and anomalously high flowrates in MB139 below the drift floor (Figure C.4). Test intervals that did not flow gas at 70 kPa (marked with stars) indicate areas with less damage and higher air-entry pressures. At these low working pressures, the lower damage “starred” area in Figure C.4 likely correlates to the brine-saturated salt region, since low-pressure gas typically does not displace brine.

Figure C.3. WIPP Small-scale mine-by experiment results (Stor-
mont et al., 1991a)

C.3 WIPP Gas Threshold Pressure Testing

Gas-threshold pressure (i.e., air-entry pressure) tests were successfully completed in Marker Bed 138 (Roberts et al., 1999, Appendix E). These tests attempted to displace brine with pressurized gas, to determine what pressure would be required to flow gas into a fractured marker bed. The test results showed air-entry pressure to be on the order of 0.2 MPa, agreeing with an empirical model relating air-entry pressure to gas permeability of the anhydrite (Davies, 1991). These tests avoided potential complicating effects that viscous fingering has on interpretation by pressuring

Figure C.4. WIPP DRZ Gas flowrate contours. Standard cm^3/min (SCCM) flowrate due to a 70 kPa applied pressure across 1 m-long 13 cm-diameter borehole interval (Borns and Stormont, 1988)

the gas-filled borehole until the pressure response deviated from unit log-log slope, indicative of pure borehole storage.

C.4 WIPP Brine Permeability Testing

Roberts et al. (1999) and Beauheim and Roberts (2002) summarized brine permeability testing performed underground at WIPP from 1988 to 1995. Tests were performed on halite, argillaceous halite, and anhydrite layers. Unlike static formation pressure at WIPP (Figure 4.18), the brine permeabilities at WIPP do not follow a simple monotonic trend (Figure C.5). These results do not separate excavation or borehole age effects, which can affect the nature of the DRZ, including brine permeabilities.

Packers and testing equipment involved a set of radial and axial strain gages, which measured borehole deformation during testing. Deformation was observed during most tests, but its effects were most significant during pulse injection or withdrawal tests (Figure C.6). Deformation included recoverable elastic response due to pressure increases and decreases, as well as slow irreversible creep closure of test intervals over many days.

Figure C.5. Brine permeability values interpreted from tests conducted in the WIPP underground, including around Room Q (Beauheim and Roberts, 2002)

Fuenkajorn and Daemen (1988) performed an extensive suite of isothermal laboratory tests related to the time-dependent borehole closure in Salado bedded salt, to attempt validation of constitutive models for predicting closure. Heated in situ accelerated borehole closure (“corejacking”) tests were performed at Avery Island (Stickney and Van Sambeek, 1984).

Constant-pressure withdrawal, pulse-withdrawal, and pressure build-up tests were performed and often analyzed together as a group to improve parameter identifiability. Roberts et al. (1999) indicated test results showed formation permeability was often stress (pressure) and distance-dependent. Although poroelastic behavior was not modeled, it was believed to be significant. A variable flow-dimension model (Barker, 1988) was used to match observed test responses. This model successfully fit the data, but flow dimension was used as a fitting parameter for the complexity of an additional physical process or parameter heterogeneity.

Strange behaviors were observed in the anhydrite layer Marker Bed 140 (20 m below the room floor). Apparent formation pressure did not stabilize through 250 days of testing (Roberts et al., 1999). This also may be due to coupled flow and geomechanical effects, specifically the interaction between the more rigid and brittle anhydrite layers and the creeping salt.

In their conclusions, Roberts et al. (1999, p. 151) cite poroelastic effects related to borehole

Figure C.6. Borehole deformation observed at WIPP during brine permeability tests, and its effects on pulse withdrawal tests (Roberts et al., 1999)

completion and deformation, including compressive tangential stress concentrations in small boreholes, as discussed by Detournay and Cheng (1993). The isothermal brine flow model of McTigue (1993) similarly assumes a non-deforming borehole. Stormont et al. (1992) used a suite of increasingly realistic finite element modeling results to the small-scale mine-by experiment, to determine effects the stress-state assumptions had on estimated permeability and porosity. In low-permeability environments, the assumptions related to initial stress state and stress state changes during the test may have an impact on estimated hydraulic properties.

The WIPP brine permeability tests performed by Roberts et al. (1999) could be reinterpreted as hydromechanical pumping tests, which use both pressure change and borehole closure as observations (Svenson et al., 2007; Schweisinger et al., 2011). Hydromechanical tests typically show an apparent increase in storage at early time due to poroelastic effects, which may be difficult to distinguish from wellbore storage effects in most tests (Schweisinger et al., 2011).

C.5 BAMBUS II & ADDIGAS Permeability Testing

The BAMBUS II Project report (Bechthold et al., 2004) covered the post-test forensic analysis performed on the Thermal Simulation of Drift Emplacement Experiment (TSDE) drift, backfill, and canisters. Significant Excavation Disturbed Zone (EDZ) characterization and permeability testing was performed as part of BAMBUS II (Bechthold et al., 2004, §4).

Gas permeability testing was performed around the TSDE experiment (on the 800-meter level), to explore the EDZ around a heated drift after cool down. In general, salt permeability was highest near the previously-heated EDZ (as high as 10^{-12} m² in the presence of extensive damage, but usually 10^{-15} m² near excavations), which was attributed to microcracking during the cool down phase post heating. No pre-test or testing data are available for comparison, but minimally disturbed salt at Asse typically has permeabilities on the order of 10^{-21} m².

Laboratory testing (acoustic wave velocity and gas permeability tests) in a 3-meter long cylindrical salt core revealed microfissuring due to post-TSDE cooling was mostly confined within 1 m of the heated drift, leading to higher porosities and permeabilities in the EDZ. These tests also revealed the salt's rock mechanical properties (Young's modulus and Poisson's ratio), as determined by sonic velocity data, were not affected by this microfissuring (Bechthold et al., 2004, p. 118). Previous geophysical studies at Asse had reached this same conclusion regarding the geomechanical stability of excavations in salt, despite extensive microfracturing (Roest, 1987).

As part of the ADDIGAS experiment (Jockwer and Wieczorek, 2008), three adjacent tests were conducted in a 20-year old Asse mine floor section (AHE drift), in a fresh floor mined 1-m deep into the old floor, and in a 2.5-year old 1-m deep re-mined floor. Test results showed gas permeability decreased smoothly with depth. ADDIGAS results confirmed the earlier AHE BAMBUS II testing, and showed removing the top of the EDZ effectively reduced the surface salt gas permeability for as much as 16 months (permeabilities remained similar to values at the same depth before excavation), but a new EDZ had developed within 33 months (Figure C.7).

Figure C.7. Gas permeability results from Asse showing removal and subsequent re-development of EDZ (Jockwer and Wiczorek, 2008).

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