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Technical Feasibility of Measuring Low-Stress, Low Strain-Rate Deformation Relevant to a Salt Repository

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Acronyms

FARX	Fluid Assisted Recrystallization
FISH	Scripting language in FLAC
FLAC	Fast Langrangian Analysis of Continua (geoengineering simulation code)
LS-LSR	Low-Stress, Low Strain-Rate
LVDT	Linear Variable Differential Transformer
mbar	milli-bars
MD	Multimechanism Deformation
MPa	Megapascals
Pa	Pascals
Pa-sec	Pascal-seconds
RH	Relative Humidity
WIPP	Waste Isolation Pilot Plant

Technical Feasibility of Measuring Low-Stress, Low Strain-Rate Deformation Relevant to a Salt Repository

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1. Introduction

Waste packages in a salt repository for spent nuclear fuel will sink during a postclosure performance period of 10,000 years or longer. The amount is predicted to be potentially significant to repository performance assessment, or not, depending on the constitutive model used. The possibility of vertical movement has been recognized for decades, but has received little attention compared to other processes such as reconsolidation and brine migration. Vertical movement of large, heavy waste packages in salt has been identified as a potentially important process in salt repository performance (Winterle et al. 2012; OECD/NEA 2000). Extensive sinking (e.g., more than 1 m per 10^4 years) could move waste packages out of the host unit especially in bedded salt, where they could be exposed to different strata and possible ground water flux.

Simulations using widely known constitutive models suggest that waste package vertical movement due to negative buoyancy would be very small (Clayton et al. 2013a,b). However, interpretation of recent salt creep tests (Bérest et al. 2005, 2012) suggests that low-stress, low strain-rate (LS-LSR) deformation could produce significant movement of waste packages. This study evaluates the technical feasibility of additional salt creep testing with the objective to extend predictive models to better represent deformation at LS-LSR conditions.

Salt rheology has been extensively studied using *in situ* observations and laboratory tests. Constitutive models have been developed and conditioned on laboratory data, and on multi-year observations of room and borehole closure. However, the strain rates associated with these observations are generally orders of magnitude greater than could be associated with vertical movement of waste packages. Also, as pointed out by Bérest et al. (2005) large deformations such as room closure produce low strain-rate deformation throughout an extensive region in the far field. A mechanism for salt creep that prevails at low temperature and LS-LSR conditions was recognized decades ago (Munson et al. 1984), but only in the past few years have attempts been made to measure its effects (Bérest et al. 2005, 2008 2012). In these tests, total strains on the order of 10^{-4} were produced at rates on the order of 10^{-12} sec^{-1} (Figure 1). The mechanism is thought to involve pressure solution because it is similar to certain behavior at greater strain rates that is known to depend on moisture content.

The challenges addressed here are to measure low strain-rate deformability of bedded Permian Basin salt and other materials, at known moisture conditions, both confined and unconfined. The effects from confining stress on constitutive behavior have been extensively studied at higher deviatoric stress levels and greater strain rates, but not at such low stress levels and low strain rates. Dependence on confinement (e.g., mean stress) could be important for a low-stress mechanism that is controlled by the distribution of moisture at grain boundaries.

The sections below present background information on salt creep, then simulations of LS-LSR creep, a research hypothesis and "strawman" testing program, and an evaluation of technical feasibility. The testing would complement previously reported studies, add more low strain-rate data to the conversation, and evaluate the effects of confinement and temperature.

2. Background

As pointed out by Jackson and Talbot (1986): "salt is one of the most intensively studied materials in rock mechanics." There is much literature comparing different types of salt, thermal responses, testing at various stress conditions, constitutive models, and so on. The following brief review focuses on observations of low strain-rate natural processes and laboratory tests, and interpretation of the operant deformation mechanisms.

2.1 Strain Rate

The spatial scale of creep deformation that could lead to waste packages sinking is intermediate between laboratory and natural diapir observations. To observe salt deformation at strain rates slower than most lab tests, we look to natural salt structures and the long-term deformation of man-made openings (e.g., tunnels and solution caverns). Jackson and Talbot (1986) provide a comprehensive summary of such observations, and the inferred strain rates (Table 1). The authors summarize this information as follows:

> "Strain rate is the proportional change in length per second of a deforming body. As a geologic datum, the mean strain rates for flow of the asthenosphere...and for crustal orogeny...have both been estimated at 10^{-14}/sec. By comparison, strain rates for *in situ* deformation of rock salt vary...over 8 orders of magnitude from 10^{-8} to 10^{-16}/sec. This wide range reflects the diverse conditions of flow. The most rapid peak rates are those of borehole closure during accelerating creep (10^{-8}/sec) whereas those of mine closures and steady-state borehole closures (10^{-9} to 10^{-11}/sec) and salt glaciers (10^{-8} to 10^{-11}/sec) are not far behind. Estimates of 10^{-13}/sec for the rate of diapiric extrusion assisted by folding are slower, and those for the most active phase of growth of diapirs driven by gravity alone are still slower at $l0^{-14}$ to 10^{-15}/sec..." (Jackson and Talbot 1986).

Scoping calculations for viscous sinking of waste packages in salt are described later in this document, with the result that strain rates of 10^{-10} to 10^{-12} sec^{-1} can be expected, leading to sinking velocity on the order of 10^{-12} m/sec. Some uncertainty remains in the definition of strain rates based on normal or shear strains. With this caveat the range of possible strain rates associated with sinking packages would overlap with subsurface diapirs. It would be slower than surface processes (salt glaciers) and faster than large-scale subsurface processes (convergent flow in the host salt formation). Package sinking could be similar in terms of strain rate to diapir penetration processes and long-term closure of larger man-made openings (mined or solution cavities) at ambient temperature.

2.2 Effective Viscosity

Effective viscosity is useful to describe the potential for salt creep, because: 1) salt typically does not exhibit yield strength or cohesion behavior (Jackson and Talbot 1986); and 2) power law creep laws can be recast in terms of effective viscosity (Weinberg 1993). An early analysis of waste canister vertical movement used a constant effective viscosity value of 5×10^{14} Pa-sec, and a temperature dependent function with viscosity of 2.5×10^{13} Pa-sec at temperatures above 110°C (Dawson and Tillerson 1978).

Analysis of natural diapirs (van Keken et al. 1993) concluded that "effective viscosity ranges from 10^{17} Pa-sec for small grain size and high-temperature salt, to 10^{20} Pa-sec for large grain size and low-temperature." This paper also introduced a two-part creep rate expression that included dislocation processes and pressure solution. The associated deformation mechanism map shows pressure solution to dominate for low strain rates up to 10^{-11} sec^{-1}, and low stress (0.1 MPa). Analysis of salt fountains such as the Kuh-e-Namak in the Zagros of Iran, indicates effective viscosity of 10^{16} to 10^{17} Pa-sec (Talbot 1998), albeit at higher strain rates than occur in the subsurface or in LS-LSR tests on core samples.

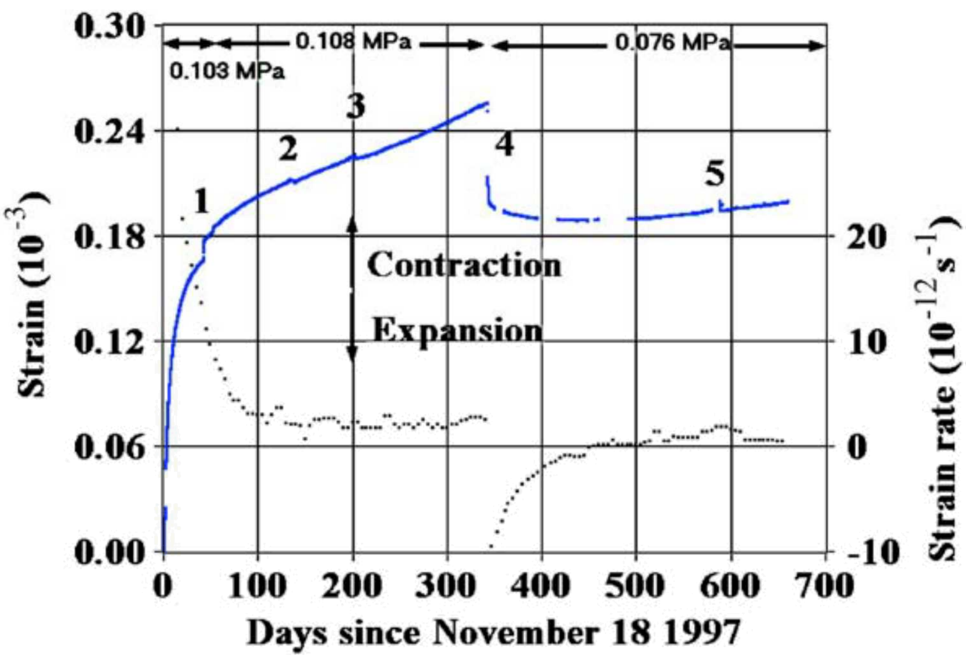
Table 1. Natural strain rates in the deformation of rock salt (from Jackson and Talbot 1986).

Environment	Strain Rate (sec^{-1})	Comments
Salt Glaciers (surface)		
Direct measurement	1.1×10^{-11} to 1.9×10^{-9}	Duration <1 yr
Comparison to theoretical profile (exposed stock and namakier)	6.7×10^{-13} to 9.0×10^{-13}	Duration approx. 10^4 to 10^6 yr (Mesozoic diapirs reactivated by upper Cenozoic tectonism)
Estimated from salt glacier morphology	2×10^{-13} to 2×10^{-8}	Duration approx. 10^4 to 10^6 yr (Mesozoic diapirs reactivated by upper Cenozoic tectonism)
Salt Diapirs (subsurface)		
Closure of mined cavity	9×10^{-12} to 10^{-9}	Duration 10 to 30 yr; up to 100°C; stress difference ~10 MPa
Closure of solution mined cavity	5.8×10^{-13}	From Benoit et al. (2009).
Peak rate of borehole closure	3×10^{-8}	Duration 90 days
Long-term borehole closure	7.4×10^{-11} to 3.5×10^{-9}	Duration ~2 yr; 100 to 160°C; stress difference 4.2 to 18.1 MPa
Topographic mound	2×10^{-14}	Duration ~11,000 yr
Comparison to theoretical profile (stock and namakier)	8.4×10^{-13}	Duration >10^6 yr
Estimates from Stratigraphic Thickness Around Diapirs		
Overall mean	6.7×10^{-16}	Duration 30 to 56 Ma
Overall range	1.1×10^{-16} to 1.1×10^{-15}	
Fastest mean	2.3×10^{-15}	Duration 1 to 13 Ma
Fastest range	6.2×10^{-16} to 3.7×10^{-15}	
Average growth for Zechstein domes (Germany)	2×10^{-15}	Duration 35 to 130 Ma

A recent numerical analysis (Clayton et al. 2013a) used the Munson-Dawson multimechanism deformation (MD) creep model (Munson 1997) both directly in a creep simulation, and as the source function for temperature-dependent viscosity in a viscous model formulation. The results for effective viscosity are both stress and temperature dependent (Clayton et al. 2013b). Using the MD model the effective viscosity at low stress and low (ambient) temperature is on the order of 10^{20} Pa-sec, and package movement is predicted to be very slow. The same analysis showed that for an effective viscosity greater than approximately 10^{16} Pa-sec, waste package sinking velocity would be less than approximately 3×10^{-12} m/sec (1 m per 10^4 yr, but proportionately greater movement over longer time periods).

2.3 Reported Low-Stress, Low Strain-Rate Salt Creep Tests

An example from Bérest et al. (2005) of long-term (22 months) creep test results is shown in Figure 1. Creep strain was defined as change in length divided by initial length. These tests were dead-loaded, and performed underground in a remote part of a salt mine with stable temperature and humidity conditions. The mechanism is thought to involve pressure solution because it is similar to deformation at greater strain rates, that is known to depend on moisture content.



Source: Bérest et al. (2005, Figure 7). Core size 7 cm dia. × 16 cm long.

Figure 1. Strain vs. time and strain-rate vs. time, for a core of Etrez salt, unconfined and axially dead-loaded at the levels shown.

The test results were interpreted using a function that was defined in two ranges (“bilinear” on a log $\dot{\varepsilon}$ vs. log σ plot) (Bérest et al. 2012). The low-stress range was Newtonian (n=1) while the higher stress range was a power law (n=4). Closure rate for a spherical opening was calculated for the bilinear case (stress threshold 4 MPa) and found to be 17 times greater than for the high-stress power law alone. Hence, the test results are potentially important for room closure and reconsolidation predictions as well as slow movement of waste packages.

2.4 Pressure Solution Mechanism

Weinberg (1993) wrote: “...several laboratory studies have indicated that dry salt deforms by dislocation creep and behaves as a power-law fluid at high strain rates” and that “traces of brine in confined salt deforming at slow strain rates cause a change in the deformation mechanism from dislocation creep to solution-transfer creep in relatively fine grained salt (Urai et al., 1986). The salt then becomes weaker and behaves like a Newtonian fluid with a viscosity that is directly proportional to the cube of grain size."

Early reference creep laws (e.g., Carter and Hansen 1983) do not predict softening at low strain rates possibly because they are conditioned to: 1) higher strain-rate data acquired to represent rock mass response to excavation; 2) unconfined or low-confinement (i.e., dilatant) tests; 3) test samples that lost moisture during handling or testing; and 4) data acquired by the relaxation test method which increases dislocation density during pre-relaxation loading (van Keken et al. 1993).

Similar conclusions were reported by Urai et al. (1986), who identified a transition mechanism with a small value of power-law stress exponent n at strain rates less than 10^{-7} sec^{-1}. They also reported that "the observed weakening behaviour agrees well with the following theoretical model for diffusion controlled solution-transfer creep:

$$\dot{\epsilon} = \frac{ABC\sigma}{kTd^3} \quad (1)$$

where $\dot{\epsilon}$ is the strain rate, σ is the applied (deviatoric) stress, A is a constant, B is a temperature-dependent diffusivity term, C is a grain boundary structure parameter, k is the Boltzmann constant, T is the absolute temperature and d is the grain size." The effects of moisture on natural deformation processes were projected to be important for strain rates less than ~10^{-10} sec^{-1}.

Spiers et al. (1986) concluded that rheology of surrounding bedded salts may be important to control long-term stability, that stresses around a repository may equilibrate faster than previously thought, and that brine migration toward hot canisters may cause softening and increased rates of sinking (which they bounded at 1 m per 10^4 yr). Thus, brine intrusion into an excavation could accelerate and possibly localize low strain-rate deformation. Spiers et al. (1990) introduced a power law for pressure solution

$$\dot{\epsilon} = 6.95 \times V_m \times 10^{-15} \frac{\exp(-24530/RT)}{T} \frac{\sigma_1}{d^3} \quad (2)$$

where

V_m = molar volume (2.693×10^{-5} m^3/mole)
Q = Activation energy (24,530 J/mole)
R = Gas constant (8.314 J/mole-K)
T = Absolute temperature (K)
σ_1 = Differential stress (Pa)
d = Grain size (m)

This power law also incorporates Newtonian behavior (n=1), with strong grain size dependence. Spiers et al. (1990) conclude in part that the relative importance of pressure solution (as judged from natural microstructural observations) diminishes during natural diapirism due to: 1) water loss during progressive shearing; 2) increased deformation rates as diapiric structures evolve; and 3) some other mechanism (possible dislocation related). For the low strain-rate test conditions of Bérest et al. (2005, 2012) and grain size of 1 cm, expression (2) yields strain rates on the order of 10^{-15} sec^{-1} at 25°C. For the same conditions it yields viscosity on the order of 10^{19} Pa-sec at

300 K. These results are too slow and viscous to represent the Bérest et al. data as discussed below.

The Newtonian form of expressions (1) and (2) contrasts with power laws conditioned on laboratory data and multi-year observations of room and borehole closure, where strain rates are much greater. For example, the compilation by Weinberg (1993) includes a power law for Permian Salado formation salt:

$$\dot{\epsilon} = 2.42 \cdot 10^{-44}\ \sigma^{4.9} \tag{3}$$

using stress units of Pa, and temperature of 300 K.

2.5 Pressure Solution vs. Recrystallization at Higher Stress and Strain Rates

Fluid assisted recrystallization (FARX) appears to counteract work hardening, such that steady state creep occurs (Peach et al. 2001). Pressure solution is comparable to, but may be distinct from FARX especially at non-dilatant confined conditions (e.g., confining pressure >5 MPa). The two mechanisms FARX and pressure solution are both moisture dependent, and were equated originally (Spiers at el. 1986) but appear to be distinct in more recent work (Peach et al. 2001). At lower confining pressures insufficient to suppress dilatancy, FARX is inhibited possibly because of grain boundary disruption or water loss. Presumed evaporation of liquid brine in the pores upon dilatancy, appears to "turn off" fluid assisted creep processes in "dry" tests, unless a brine pore pressure is imposed externally. Also, both mechanisms may be complicated by "ripening" or "blunting" behavior as contacting grain boundary asperities dissolve and widen (possibly similar to phenomena observed by Hickman and Evans 1995) or as grain boundaries heal (a transition proposed by Lehner 1995). This discussion suggests that LS-LSR creep may fit into a framework that includes recrystallization behavior at higher stress conditions, and that measurement of low strain-rate deformation at confined conditions could help to discern the relationship.

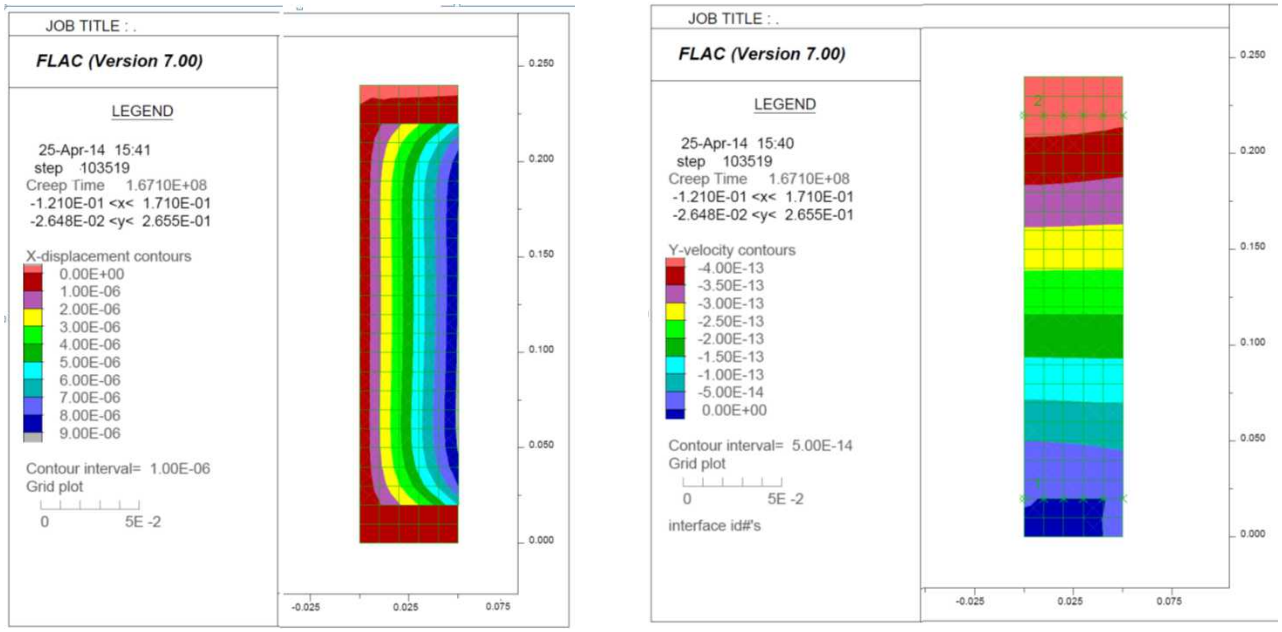
3. Simulations and Comparative Analyses

Simulations are presented with several objectives: 1) interpret published core data in terms of effective viscosity, to simplify other simulations; 2) compare core data to simulations with widely known existing constitutive models; 3) evaluate stress conditions in the salt around heavy waste packages in a salt repository; and 4) evaluate the impact of Newtonian LS-LSR creep behavior around simulated repository openings. The results establish that LS-LSR creep behavior is not described by existing models, that the unconfined test data are relevant to similar stress conditions where they occur around a repository, and that LS-LSR behavior could significantly change simulated deformations around a repository if it occurs in the far field, or in the near field after reconsolidation. Simulations were performed using the FLAC code (Itasca 2011) with model geometry, boundary conditions and constitutive models as described below.

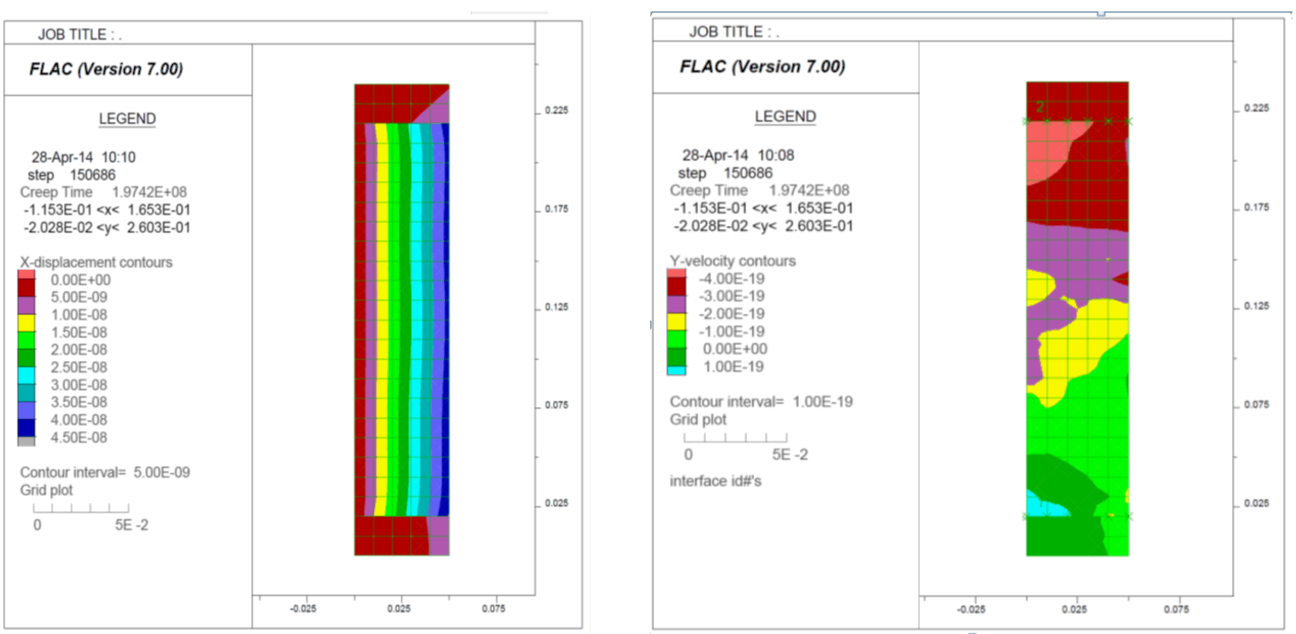
3.1 Simulation of Laboratory Creep Tests

Core test data from Bérest et al. (2005, 2012; strain rate vs. stress magnitude) are compared to an axisymmetric problem with similar geometry (Figure 2a). Using a viscoelastic model and adjusting the effective viscosity, yields a value (1.6×10^{16} Pa-sec) that reproduces the reported 2×10^{-12} sec^{-1} strain rate with an applied stress of 0.1 MPa. Steel endcaps are included in the model, with zero-strength, limited-friction interfaces at the sample contacts (15° friction angle). Sample size is 10 cm dia. by 20 cm, with 5 years simulation time.

The MD model was coded as a FISH file in FLAC, populated with WIPP salt parameters (Jove-Colon et al. 2012) and run for the same axisymmetric problem. The results show a strain rate of 2×10^{-18} sec^{-1}, or about 10^6 times smaller than the observed rate (Figure 2b).



a) Viscoelastic (strain rate 2×10^{-12} sec^{-1}, viscosity 1.6×10^{16} Pa-sec).



b) Munson-Dawson (strain rate 2×10^{-18} sec^{-1}). The variability in velocity is associated with very small values on the order of 10^{-19} m/sec.

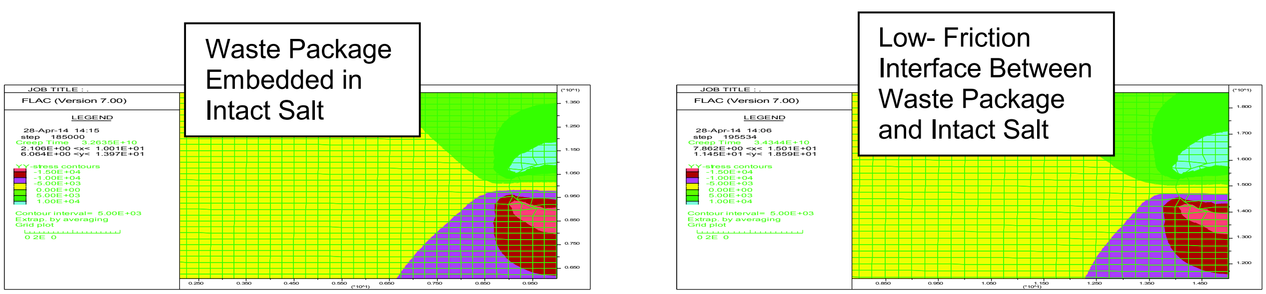
Figure 2. Simulation of published core creep test results using (a) viscoelastic and (b) MD constitutive models, showing radial displacement (left) and axial velocity (right) for unconfined axial loading of 0.1 MPa.

3.2 Evolution of Stress Conditions and Waste Package Sinking

Stress conditions in the vicinity of a heavy waste package embedded in salt are considered for comparison to test conditions. The embedded geometry represents long-term evolution of the repository. The crushed salt backfill is assumed to fully reconsolidate due to closure of the mined opening, with properties similar to intact salt. The uniform salt approximation is appropriate for thick salt beds and does not account for stratigraphic heterogeneity (marker beds, interfaces, anhydrite seams, etc.).

Using FLAC, a cylindrical inclusion with steel properties is embedded in uniform salt. Density of the salt is set to a very small value (effectively zero) and the effective density of the waste package is adjusted by subtracting the intact salt density (yielding 3,000 kg/m^3 average density for the package). The effect of gravity then exerts only the negative buoyant force on the package. The upper boundary for this model is a free surface, the bottom is fixed in the x-direction, and the sides are fixed in the y-direction.

The problem of waste package support by surrounding salt is quasi-static so that instantaneous stress conditions are the same (or similar) for elastic, viscoelastic, and viscoplastic creep constitutive laws. Maximum stress is calculated to be approximately 2×10^4 Pa, for both the embedded case and the case of interface elements interposed between the package and the salt (Figure 3). The interface is represented using liner elements in FLAC, with assigned nominal interface normal and shear stiffness values, zero tensile strength, and shear resistance prescribed by a friction angle (15°C) with zero cohesion.



Notes: Calculations were run to approximately 1,000 years, with viscosity of 1.6×10^{16} Pa-sec, and densities adjusted so that only buoyancy effects are calculated. Package diameter is 2 m, with density adjusted so that loading is limited to negative buoyancy of the waste package .

Figure 3. Close-up views of vertical normal stress caused by negative buoyancy around a heavy waste package in a viscoelastic salt medium (symmetry model), with the package embedded (left) or separated from the salt by a low-friction interface (right).

Given the uncertainty of frictional and cohesive properties at the package-salt interface during vertical movement, an upper bound was developed for the normal stress under a waste package.

Any bonding or friction that could suspend the package, decreasing the normal stress below, is eliminated by situating the package on a free surface (Figure 4). This geometry increases the maximum bearing stress to approximately 6×10^4 Pa.

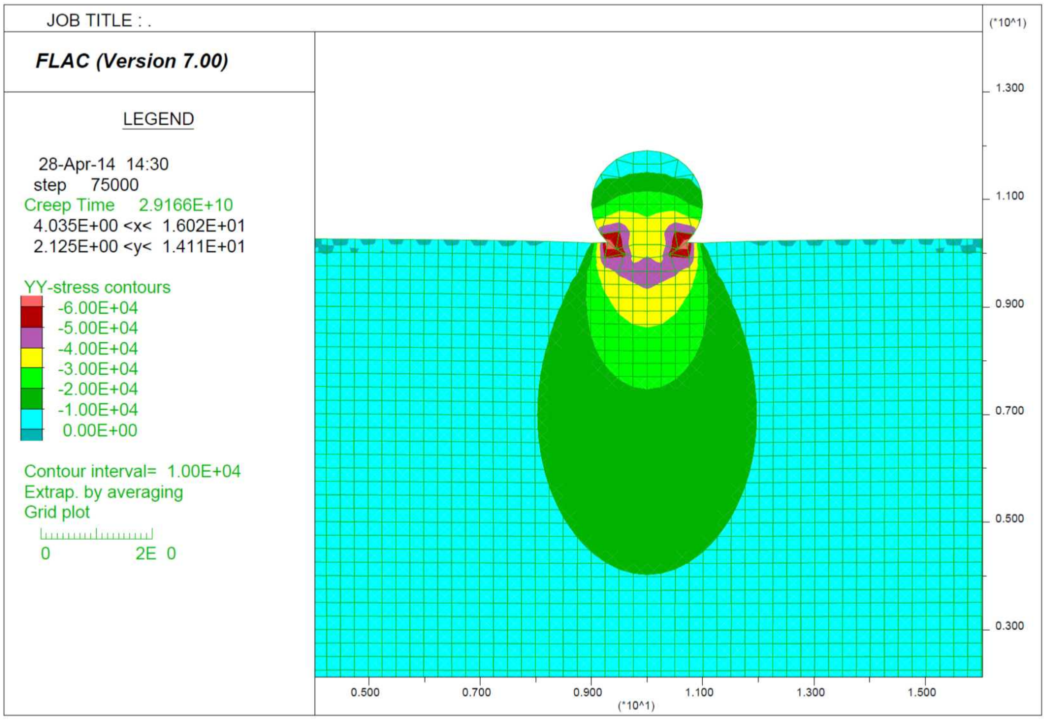


Figure 4. Reasonable-bound stress magnitude calculation for a heavy waste package resting on the free surface of a viscoelastic salt medium, bonded over 1.5 m of the lower circumference, after approximately 10^3 years of deformation.

A final scoping calculation compares the velocity of vertical movement of an embedded waste package, with the velocity and strain rate observed in core tests by Bérest et al. (2005, 2012). The viscoelastic model is calibrated to test data (effective viscosity of 1.6×10^{16} Pa-sec). Density adjustments are used to isolate the stress conditions associated with negative buoyancy. The resulting downward waste package velocity (approximately 6×10^{-13} m/sec) is associated with an average strain rate on the order of 10^{-13} sec^{-1} over a circumferential path around the package. Alternatively, the maximum strain rate is on the order of 10^{-12} sec^{-1} in a region at the furthest edge of the package (Figure 5). The cylindrical package produces a slow circulation flow that affects the entire model domain.

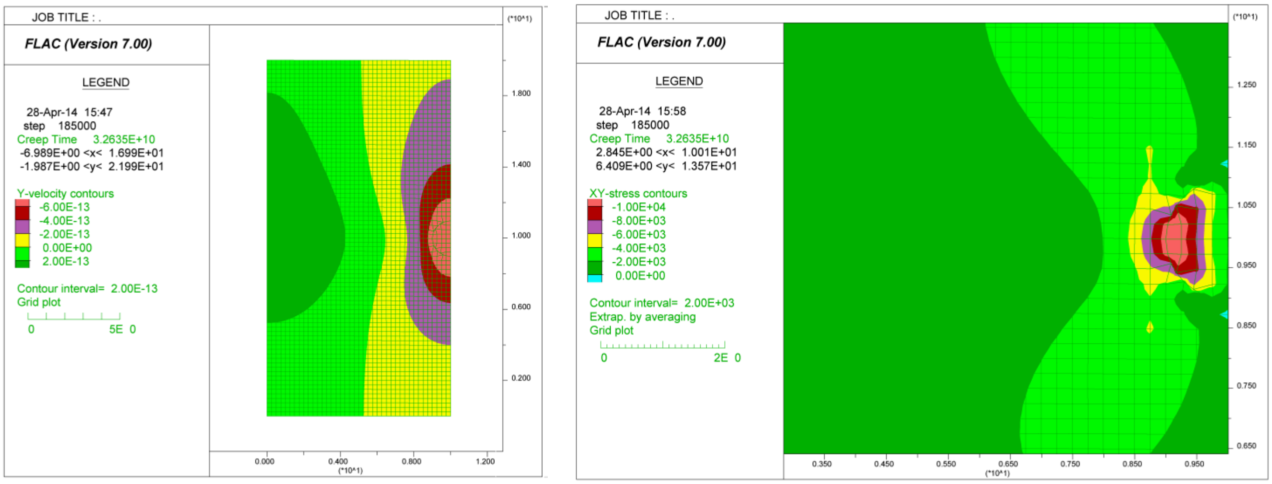


Figure 5. Viscoelastic simulation of package vertical movement, after approximately 10^3 years, showing vertical velocity (left) and a close-up of x-y shear stress (right).

3.3 Spliced Power-Law Constitutive Model

To explore the modeling implications of these different laws, expression (3) is spliced with a Newtonian power law (n=1) that is constrained by data from Bérest et al. (2005, 2012). The intercept of the segments with different slopes on a log-log plot, as shown in Figure 6a, is constrained by the Bérest et al. data so that the transition stress is σ = 8 MPa. This transition value is model dependent, and does not signify a sharp transition in salt response. The approach is similar to that of Bérest et al. (2012) who analyzed the LS-LSR deformation of a solution-mined storage cavity using a transition stress of 4 MPa.

The spliced constitutive model is used in the FLAC code with a grid representing a cross-section through a repository drift (Figure 6b). The model domain is a vertical cross-section through a single repository panel, with 30-m spacing between parallel drifts. The drift opening is filled at the time of excavation and emplacement, with crushed salt at initial porosity of 36% and creep-consolidation behavior represented by the *cwipp* constitutive model in FLAC (Itasca 2011). A 2-m diameter waste package rests on the floor. The package is assigned the density of steel (8×10^3 kg/m^3, greater than the average density expected for large, heavy waste packages ~5×10^3 kg/m^3).

The simulation is run for 1,000 years, and vertical displacements plotted for the drift crown and the invert below the waste package (Figure 7). The plots show the early displacements when the opening is excavated (down at the crown, up at the floor), followed by creep response as the opening closes and the backfill consolidates. The figure compares results with the original Norton-Hoff law for Salado salt (Weinberg 1993) with the spliced model. The Norton-Hoff law produces gradual creep response, then stability as the backfill approaches intact density and the stress state returns to lithostatic. By contrast, the spliced model exhibits rapid creep response, followed by steady-state downward movement of the waste package and the surrounding salt. The velocity of this movement is approximately 1 meter per 10^4 years.

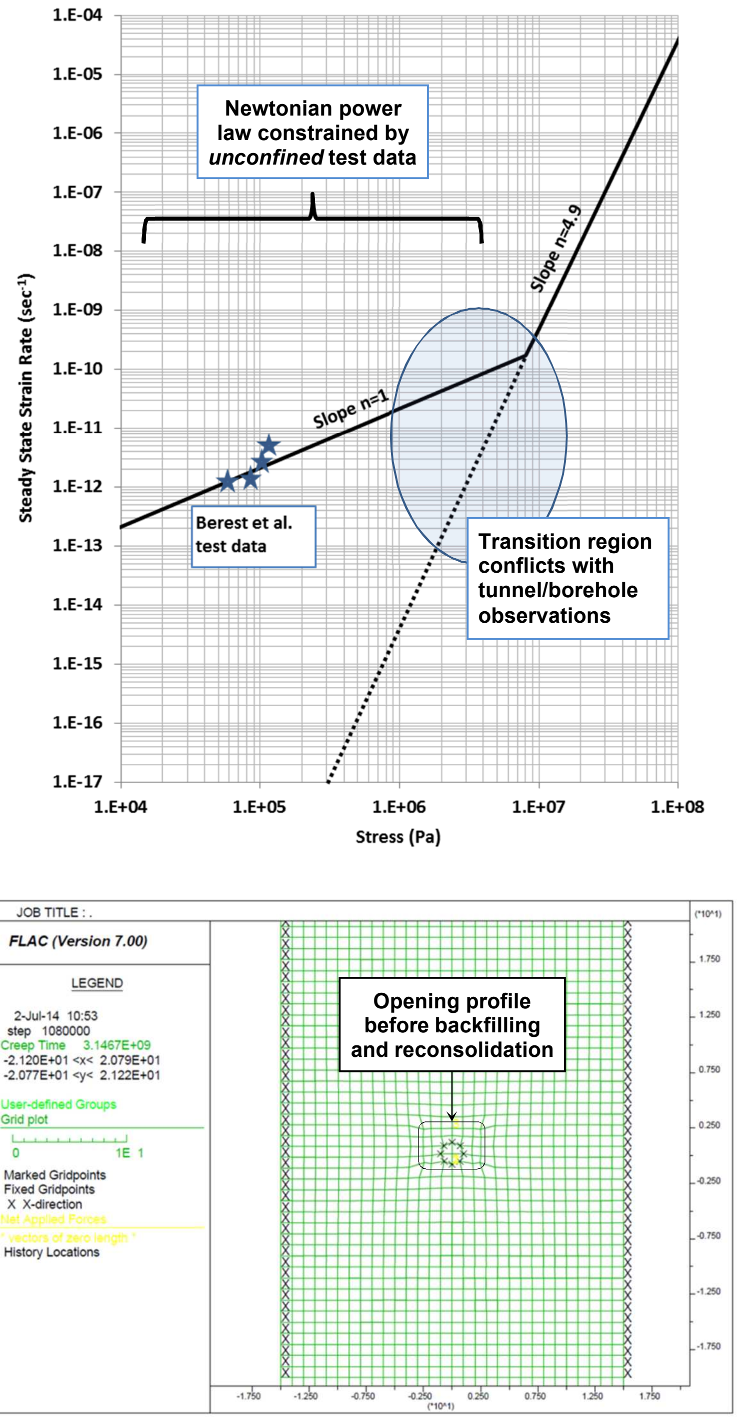
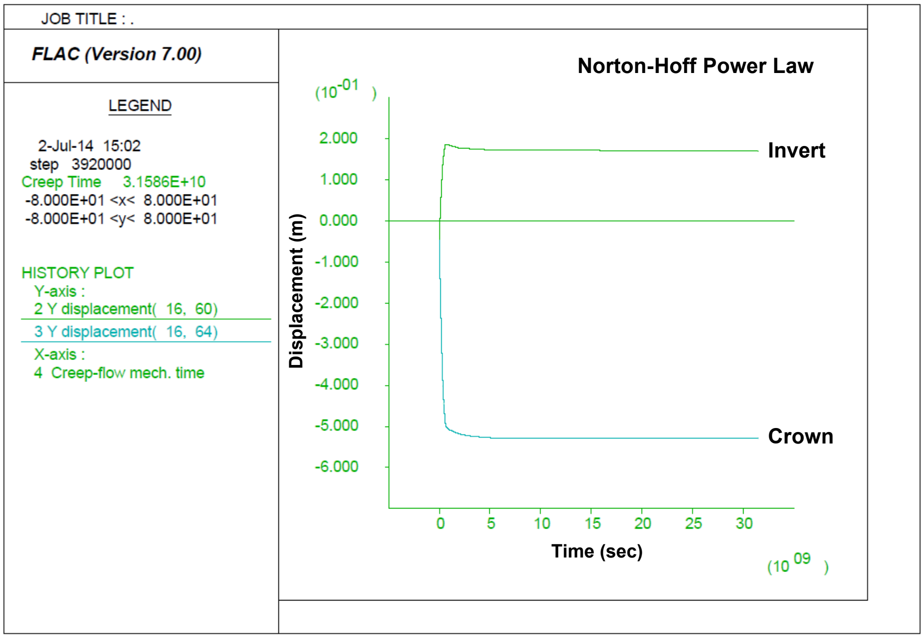
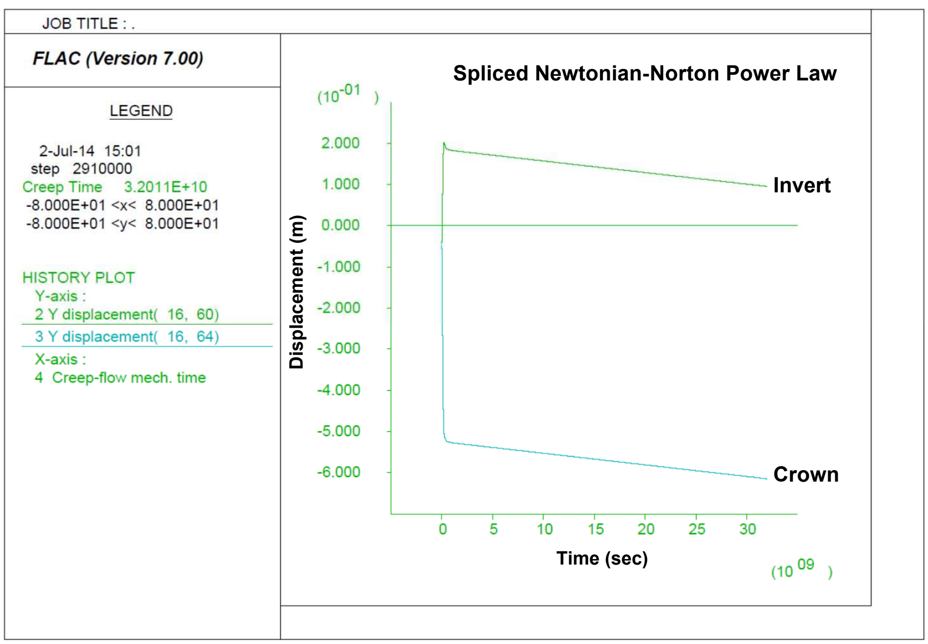


Figure 6. Modeling details: (a) spliced Norton-Hoff and Newtonian constitutive laws, and (b) FLAC model grid used in comparative analysis.



(a)



(b)

Note: In each plot the crown moves downward and the floor upward in response to initial excavation of the drift opening, followed by long-term sinking of the package (and its surroundings) in the spliced case. Duration of simulations is approximately 1,000 years.

Figure 7. Time dependent crown and invert displacements for a rectangular waste emplacement opening in salt, for 100 years, using: (a) a Norton-Hoff power law, and (b) a Norton-Hoff power law spliced to a Newtonian LS-LSR power law at stresses less than 8.1 MPa.

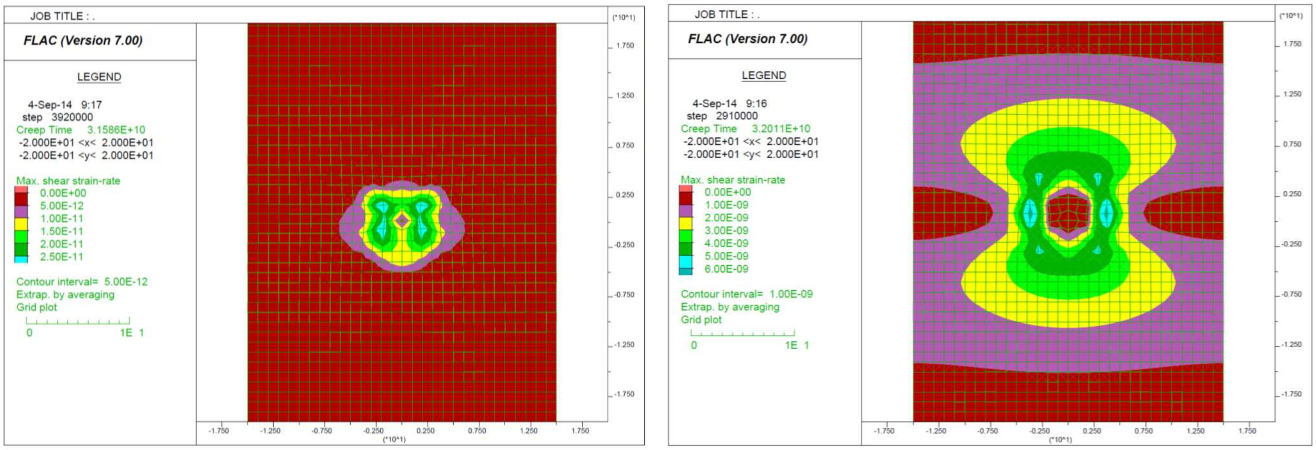


Figure 8. Maximum shear strain rate at 10^3 years, for a Norton-Hoff power law (left), and a Norton-Hoff law spliced to a Newtonian power law at stresses less than 8.1 MPa (right).

The maximum shear strain rate (Figure 8) further represents the differences between the Norton-Hoff law and the splice power law models. The strain rate for the single Norton-Hoff power law shows shear strain localized to the near field, and the deformation field is slowly evolving even at 10^3 years. Much of the strain at this point in the evolution is taking place in the backfill. With the spliced power law the maximum shear strain rate occurs in the host rock, and the rate is 2 orders of magnitude greater than the single power law. Moreover, this deformation field develops rapidly, less than 100 years after emplacement.

3.4 Summary of Comparative Analyses

The LS-LSR creep tests on core reported by Bérest et al. (2005, 2012) show highly compliant viscous behavior, which can be expressed as effective viscosity of 10^{16} Pa-sec (Section 3.1) and compared with natural salt creep (Sections 2.1 and 2.2). The calculated normal stress magnitude in the salt, developed only from the waste package weight (corrected for salt density) is similar to loading conditions in the LS-LSR core creep tests (Section 3.2). However, the LS-LSR salt creep tests were unconfined, while stress conditions in the repository host rock are more complicated both spatially and directionally. Ignoring any effects from confinement (mean stress) the waste package sinking velocity with the calibrated viscoelastic model (6×10^{-13} m/sec) and the spliced power-law model (3×10^{-13} m/sec), yield long-term movements on the order of 1 m per 10,000 years. These results conflict with previous analyses using the widely known MD mechanistic creep law with temperature dependence (Clayton et al. 2013a), which predicts much less movement.

The rapid creep response calculated with the spliced model (Section 3.3) is unrealistic. This modeling exercise shows that if LS-LSR creep can occur throughout the rockmass, then salt in the far field creeps rapidly, shifting load to the near field around openings where salt creep accelerates because of greater stress. This situation leads to questions about the role of the mean stress, i.e., confining stress, in constitutive models that include LS-LSR behavior.

If the LS-LSR creep strain rate is attenuated by confining stress, then existing creep models accurately describe major deformation processes, and sinking of DPC-based packages would be insignificant. If LS-LSR creep occurs at confined as well as unconfined conditions, then waste packages could sink at velocities on the order of 1 m per 10^4 years.

This assessment does not take into account the effects of heating, which lasts only about 1,000 years but could increase strain rates by 2 to 3 orders of magnitude at temperatures 100 to 200°C above ambient, respectively (activation energy of 50.2×10^3 J/mol-K for dislocation creep; Weinberg 1993). Temperature effects were shown to be small with the MD constitutive model (Clayton et al. 2013a,b). If LS-LSR creep rates are important after reconsolidation, and similarly accelerated by heating, then waste package sinking could far exceed 1 meter in 10,000 years. The Arrhenius temperature dependence of existing models is empirically based, from tests that exercised dislocation creep mechanisms, so this activation energy may not apply to LS-LSR creep.

4. Feasibility of a Testing Concept

This section discusses technical challenges associated with LS-LSR salt creep tests. A "strawman" testing program is described, and the technical challenges are discussed and prioritized. It begins with the statement of a research hypothesis that provides context and helps to focus the discussion on specific aspects of testing such as confining pressure, moisture content, etc.

4.1 Research Hypothesis

Pressure solution occurs at grain boundaries where they are bridged by contacts. A film of moisture covers each contact, and remains even after salt cores are drilled and thus unloaded (dilation that occurs with unloading can produce unsaturated conditions in grain-boundary porosity). Dissolution and solute diffusion can occur in the brine film as deduced by Hickman and Evans (1995). When cores are subjected to loading, framework stress is concentrated through the grain boundary contacts. The more highly stressed salt at the contacts dissolves into the brine film and diffuses outward to the edge of the contact where stress is smaller.

Following the model of Rutter (1976) the convergence rate at each circular contact is proportional to the contact force, and inversely proportional to the 4^{th} power of the contact radius. As the mean stress increases, contact force increases, the contact radius grows, and pressure solution slows down. The physical interpretation is that diffusive transport through the brine film slows down as the path length increases. To help quantify the effect, volume strain observed in the laboratory at low confining pressure could be interrogated to estimate contact abundance and radius. Using this conceptual model, the slope of an experimentally determined volume strain vs. confining pressure curve, at pressures in the range of interest (e.g., 0.1 to 5 MPa), would be inversely proportional to contact radius assuming a grain size and the number of contacts between grains. By substituting, an inverse relationship between the rate of pressure-solution creep and confining pressure could be developed. In this way the LS-LSR data of Bérest et al. (2005, 2012) could be accommodated, while higher stress, higher strain-rate simulations show behavior more typical of that observed in large-scale *in situ* tests underground.

This semi-mechanistic constitutive modeling approach could be tested and validated using LS-LSR creep tests at confined stress conditions. An observation that LS-LSR creep slows significantly at confined conditions would greatly improve understanding of grain boundary effects. The effect of sample moisture on LS-LSR deformation also needs to be measured, to evaluate the extent to which the mechanism involves salt dissolution, and help to verify the deductions of Hickman and Evans (1995).

4.2 Testing Concept

A multi-year testing program would develop instrumentation and test fixtures, prove them in an underground laboratory, acquire and prepare core samples, and perform multi-year creep tests. Tests would be performed first to replicate published behavior for unconfined salt cores at ambient temperature, then to verify the effect of adding a compliant sample jacket without applied confining pressure, then with different levels of applied confining pressure, and finally at elevated temperature.

The test apparatus would be similar to that depicted by Bérest et al. (2005, 2012) consisting of end-fixtures for the core sample, multiple axial displacement transducers, and fixtures for support in an underground room and application of dead load (Figure 9). Displacement transducers would be off-the-shelf, with useful resolution of 0.01 μm and temperature coefficients on the order of 1 μm/C° or better. Total creep displacement for a typical core sample (7.6 cm diameter and 15 cm length) is expected to be on the order of 10 μm. Temperature measurements of appropriate accuracy would be made proximal to each sample, within the confining vessel.

For application of confining pressure the entire apparatus including transducers and dead-weights would be submerged in a pressure vessel and subjected to hydrostatic pressure (e.g., water pressurized by a gas-over-fluid accumulator or a pressure reservoir at least 100 m above). Transducers for confined tests would be submersible, with critical elements isolated from the confining fluid.

The test room would be isolated from mine ventilation, mining or maintenance activities, unauthorized human access, and other potential disturbances. A room location would be selected distant from other underground activities. Bulkheads would be set up to prevent or limit air circulation. Energy sources such as electronics would be located outside the test room to limit temperature effects. The apparatus could be situated within a boring (Figure 9) to provide additional insulation. Temperature regulation in the underground test room would need to be a fraction of 1 C°. Humidity regulation would be less important with jacketed samples, but is expected to be ±2% or better once stable conditions are achieved.

Samples would be acquired from selected horizons within the host salt, and multiple samples would be collected from the same setting to limit sample-to-sample variability in composition or condition. Samples would be cored and immediately wrapped to limit the loss of in situ moisture. Cores would be prepared for testing, by dry sawing and dry surface grinding. All core storage and transport would be maintained at stable temperature and humidity conditions (e.g., 27°C and 75% RH). Extra samples would be prepared, stored, and periodically selected for sacrificial tests to determine moisture content and flatness of core ends.

Unconfined tests would be implemented first, followed by confined tests, then heated tests in successive years (Figure 10). Overall multi-year program cost would be approximately $1M. Additional effort could be expended to develop and implement instrumentation for measuring transverse displacement (i.e., volume strain) of cores for both unconfined and confined tests.

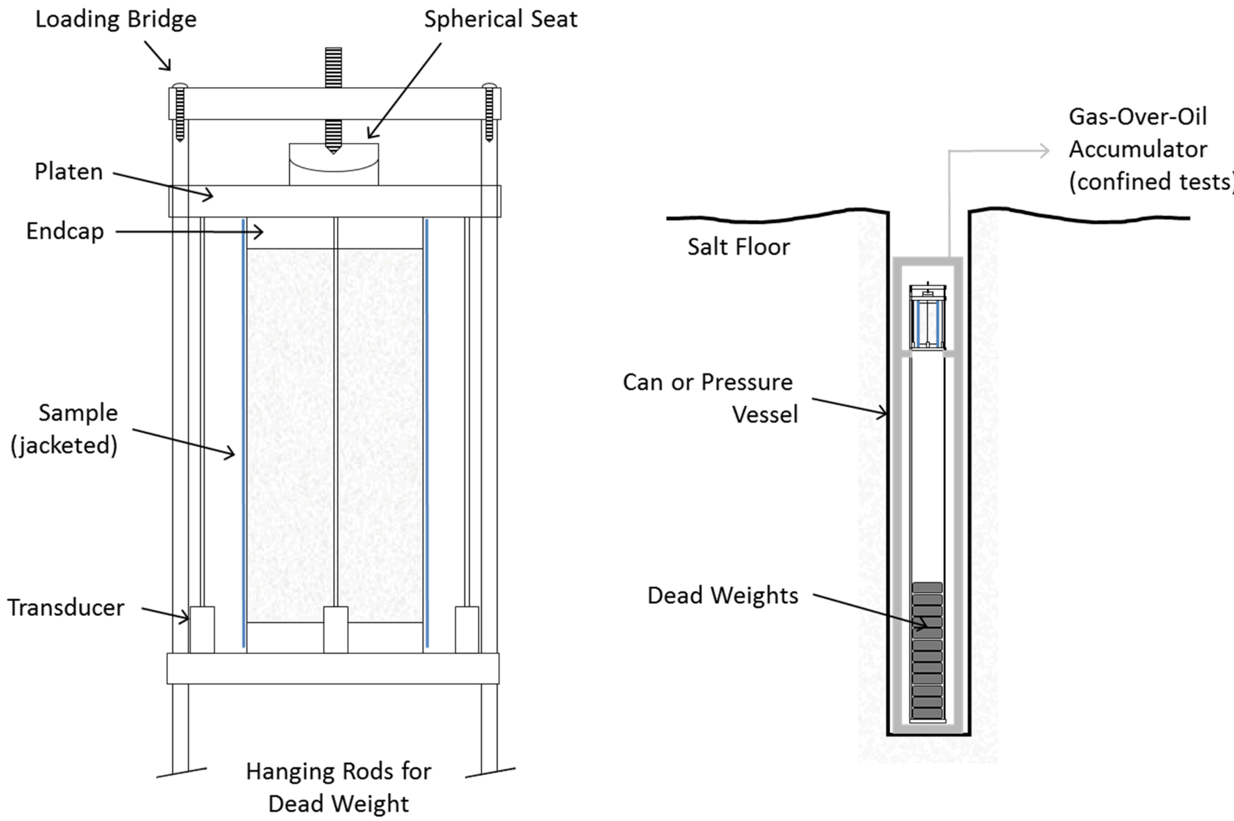


Figure 9. Schematic of LS-LSR creep test apparatus (data acquisition not shown).

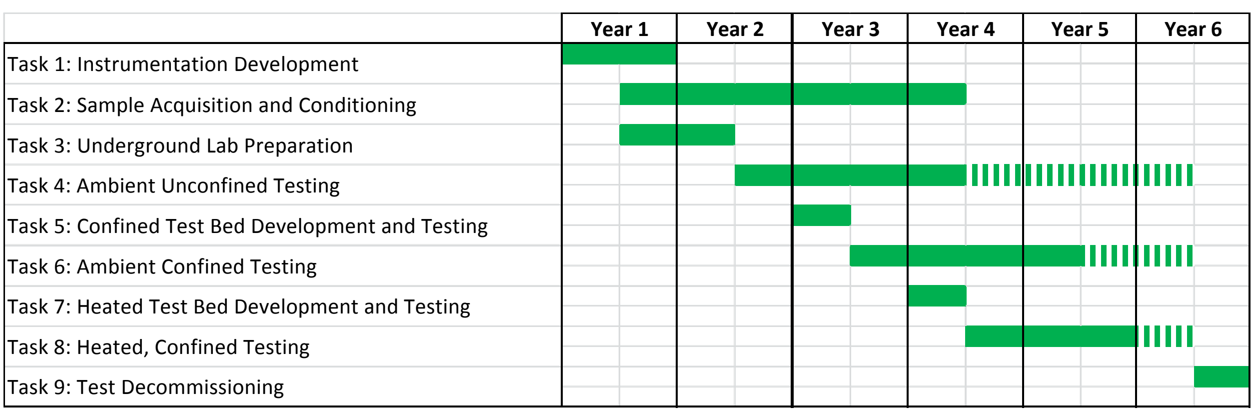


Figure 10. Notional schedule for multi-year LS-LSR creep testing program.

4.3 Challenges to Experimental Method and Resources

The unconfined, ambient temperature tests are feasible in principle because they have been performed by Bérest et al. (2005, 2012) with some success. Replication of these tests, possibly including one or more witness samples of the same Avery Island salt, would be an early goal of testing such as that described above. Some potential problems with developing a similar testing capability are:

- **Underground Laboratory** – Availability of an underground laboratory in salt with a suitably isolated test room, and without interference from underground operations. An underground test room is needed to provide the requisite stability of temperature and humidity, and for isolation from vibration. A room in salt is needed because other media tend to have too much humidity because of their water content and permeability to ground water. Various evaporite rock types and salt mineral assemblages could be acceptable because most evaporites are deliquescent, with affinity for moisture that is similar to sodium chloride.
- **Salt Core Samples** – Acquisition of salt core samples with appropriate quality and consistent provenance. Cores that were acquired from different stratigraphic positions may vary with respect to the salt minerals present and the amount of clay. Cores that have been stored at unfavorable conditions (e.g., exposed to the elements or in buildings with large seasonal fluctuations in humidity) may have altered moisture content or other changes in physical properties. Whereas replicated measurements are needed for confidence building, these tests are expensive and time consuming compared to more conventional creep tests, so the consistency of sample materials is a special concern.
- **Displacement Instrumentation** – There is uncertainty as to the possibility that the same displacement instrumentation can be selected for unconfined testing, and also for use in a confining fluid at pressure, in later stages of a testing program. While the Bérest et al. (2005, 2012) unconfined experiments can be performed using off-the-shelf instrumentation (e.g., linear encoders), similar measurements in a pressurized fluid environment have not yet been demonstrated. Note that if the research hypothesis stated above is essentially valid, the LS-LSR creep rate will decrease with confinement. Off-the-shelf submersible displacement transducers are available but tend to be linear variable differential transformer (LVDT) systems. These can incorporate an isolation barrier by design, but typically achieve slightly inferior resolution and accuracy. Also, application of confining pressure can distort LVDT components (as well other transducer types), so that calibration at pressurized conditions may be required. Notwithstanding these potential problems, success is likely because confining pressure could be low (a few MPa), LVDTs can be read to very small resolution, and the underground testing environment will be very stable limiting electronic noise.
- **Jacket Deformability** – The unconfined tests will include tests with jacketed samples, with the objective to evaluate the slight confinement and isolation from humidity that a jacket provides. Highly compliant jacket materials exist that do not involve stretching or shrinking over the sample, and have been used extensively in other testing programs. A problem might emerge if the phenomenology of LS-LSR creep is somehow sensitive to environmental conditions that are changed by use of a jacket.

- **Data Interpretation** – The research hypothesis presented above is a conceptual target for testing but requires further development for application to test data. This could include quantification of salt parameters such as grain size and grain-boundary contact density, which are poorly defined or difficult to directly measure or observe. Different hypotheses will be needed as alternative models, especially if the observed data are not well represented or can be represented only with unrealistic parameter settings.

The overall goals of the testing program would be to advance the state-of-the-art in creep testing and modeling, and to investigate LS-LSR creep under confined conditions and at elevated temperature. Some potential problems with extending the ambient, unconfined testing capability are:

- **Stable Confining Pressure** – The tests of Bérest et al. (2012) were shown to be sensitive to changes in dead loading, as small as 0.05 MPa (Figure 1). Hence, confining pressure would need to be controlled with stability on the order of 0.01 MPa or better (random variability). This is comparable to barometric fluctuation amplified by variation the in mine ventilation rate (e.g., ±0.0025 MPa or 25 mbar). Accordingly, a highly stable pressure source would be needed, such as a fluid reservoir at least 100 m above the test room, connected by leak-proof tubing. A gas-over-fluid accumulator could be effective, but subject to leakage and fluctuation with temperature.
- **Volumetric Displacement Measurement** – The tests of Bérest et al. (2005, 2012) measured axial displacement only. Volume strain is also of interest to understand dilatant behavior including compression of dilatant grain-boundary porosity. The LS-LSR creep mechanism is probably not isochoric if grain-boundary processes predominate. Transverse strain measurements are common in confined rock mechanical testing, but not with the resolution and accuracy that could be needed for LS-LSR creep tests. The accuracy of transverse displacement measurements is typically less than for axial displacement, and volume strain is proportional to the square of changes in diameter or circumference (thus exacerbating measurement errors). Another potential problem is instability of the jacket material where it is contacted by the displacement measuring components (rock mechanics tests have used metal buttons projecting through the jacket). Conventional solutions need to be tested and evaluated for use in long-term LS-LSR creep testing.
- **Strain Magnitude and Testing Duration** – With low strain rates, accumulation of significant strain could take much longer than the practical duration of a creep test. Thus, the effect of grain-boundary void closure could take many years to observe. This potential problem is inherent to the idea of LS-LSR mechanisms, and not specific to test design or instrumentation (except if tests are actually performed to very long duration). It indicates a need for testing under confined conditions up to several MPa, and volume strain measurements, for process-level interpretation without the benefit of long-term (e.g., 10-year) data.
- **Elevated Temperature** – As noted previously, the thermal period in a repository for heat-generating waste would last only about 1,000 years but could increase strain rates by up to 3 orders of magnitude during much of that time. Thus, strain accumulation during the thermal period could be equivalent to 10^4 to 10^5 years at ambient temperature, if the LS-LSR mechanism exhibits temperature dependence comparable to dislocation creep. Extrapolating LS-LSR measured strain rates, this corresponds to 1 to 10 m of waste package sinking during

the thermal period. Such accumulation may not occur due to the effects of confinement, or moisture redistribution, or heave cause by thermal expansion. However, direct observation could be needed to understand whether the LS-LSR mechanism is important at elevated temperature. Testing at elevated temperature is generally more difficult because of imperfect temperature control, especially in underground environments. This is an engineering challenge that can be addressed with proportional temperature controllers, thermal insulation, and uninterruptable power supply.

The foregoing discussion is presented as two lists to discriminate lesser problems that might be encountered with initial ambient, unconfined tests, from more fundamental technical challenges that would be encountered with confined tests, measurement of transverse strain, and elevated temperature. The recommendations of this evaluation are presented in a similar manner.

5. Recommendations

In accordance with the above categorization of potential problems, the initial priorities of a testing program should be replicating published results, instrumentation development, control of sample variability and conditioning, jacket effect (unconfined), and model development. The next priority should be confined tests because the stress state of salt around underground openings is confined, and the availability of creep test data for confined conditions is the principal difference between LS-LSR creep and dislocation creep models (e.g., Figure 6a). Confined tests will require additional apparatus and instrumentation development, and will be more complex to perform.

The final priorities are judged to be volume strain measurement for LS-LSR creep tests, and testing at elevated temperature. The former will be a challenge to produce sufficiently accurate measurements, while the latter will be challenge to control test conditions (primarily temperature) and characterize instrument responses.

Addressing the initial priorities is technically feasible, particularly since LS-LSR test results are already published. If test development proceeds in a stepwise manner, confined tests should also be feasible particularly if confining fluid pressure can be controlled by passive means such as an elevated reservoir, and the pressure response of displacement transducers is minimal.

The final priorities are more difficult and will take time. The instrumentation and apparatus development activities for volume strain and elevated temperature should be undertaken separately and started early so as to simplify implementation when the other creep testing objectives have been achieved.

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