Laboratory Evaluation of Damage Criteria and Creep Parameters of Tioga Dolomite and Rock Salt from Cavern Well No. 1

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Laboratory Evaluation of Damage Criteria and Creep Parameters of Tioga Dolomite and Rock Salt from Cavern Well No. 1.

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ABSTRACT

A suite of laboratory triaxial compression and triaxial steady-state creep tests provide quasi-static elastic constants and damage criteria for bedded rock salt and dolomite extracted from Cavern Well No.1 of the Tioga field in northern Pennsylvania. The elastic constants, quasi-static damage criteria, and creep parameters of host rocks provides information for evaluating a proposed cavern field for gas storage near Tioga, Pennsylvania. The Young’s modulus of the dolomite was determined to be $6.4 \times 10^6$ psi, with a Poisson’s ratio of $0.26 \pm 0.04$. The elastic Young’s modulus was obtained from the slope of the unloading-reloading portion of the stress-strain plots as $7.8 \times 10^6$ psi. The damage criterion of the dolomite based on the peak load was determined to be $J_{2}^{0.5} = 3113 + 0.34 I_{1}$ (psi) where $I_{1}$ and $J_{2}$ are first and second invariants respectively. Using the dilation limit as a threshold level for damage, the damage criterion was conservatively estimated as $J_{2}^{0.5} = 2614 + 0.30 I_{1}$ (psi). The Young’s modulus of the rock salt, which will host the storage cavern, was determined to be $2.4 \times 10^6$ psi, with a Poisson’s ratio of $0.24 \pm 0.07$. The elastic Young’s modulus was determined to be $5.0 \times 10^6$ psi. Unlike the dolomite specimens under triaxial compression, rock salt specimens did not show shear failure with peak axial load. Instead, most specimens showed distinct dilatancy as an indication of internal damage. Based on dilation limit, the damage criterion for the rock salt was estimated as $J_{2}^{0.5} = 704 + 0.17 I_{1}$ (psi). In order to determine the time dependent deformation of the rock salt, we conducted five triaxial creep tests. The creep deformation of the Tioga rock salt was modeled based on the following three-parameter power law as $\dot{\epsilon}_s = 1.2 \cdot 10^{-17} \sigma^{4.75} \exp (-6161/T)$, where $\dot{\epsilon}_s$ is the steady state strain rate in $s^{-1}$, $\sigma$ is the applied axial stress difference in psi, and $T$ is the temperature in Kelvin.
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1. Introduction

In the interest of providing safe, reliable, and economical supplies of natural gas to northeastern U.S., Market Hub Partners (MHP) is planning to build a natural gas storage facility in bedded salt near Tioga, Pennsylvania. The cavern field will be located in the Salina Salt Formation, which is overlain by dolomite layers, and the Oriskany sandstone. The Oriskany is a depleted gas reservoir currently being used to store gas.

Twelve triaxial tests for each rock type and six creep tests for the rock salt were conducted to determine the elastic and fracture responses of the dolomite and rock salt and to determine the steady-state creep parameters for the salt. Table 1 shows the test matrix for two different types of laboratory tests outlined in this report. The objectives of the laboratory experiments were to:

1) characterize elastic constants (Young’s modulus and Poisson’s ratio) which best represent the properties of dolomite and rock salt using triaxial compression tests,
2) describe the damage criteria of dolomite and rock salt represented by the invariant model,
3) estimate the time dependent deformation of the rock salt.

The detailed geological descriptions of the core and sample locations can be found in Appendix A. The grey dolomite appears to be organic rich and locally shaly. Very thin beds of anhydrite are common. The Tioga rock salt (or halite) has well-developed cleavage. The rock salt is generally light gray and coarser grained at the top and progressively gets finer grained and darker with depth. The salt gets darker because of a decrease in grain size and more importantly a change from predominately gray dolomite / anhydrite impurities to a predominantly black shale insoluble content. Although there is some insoluble material within salt grains, the bulk of the insoluble material is attenuated between the grains at or near the grain boundaries (K. Looff, 2001).

The laboratory experimental data provide the quasi-static mechanical properties and creep behavior of the host rocks necessary for the design, construction and operation of the future gas storage caverns.
Table 1. Planned test matrix and sample locations for the laboratory testing of Tioga dolomite and rock salt from Cavern Well No. 1, Pennsylvania.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Rock type</th>
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<th>Sample diameter (inch)</th>
<th>Sample length (inch)</th>
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TC- Triaxial Compression  
UC-Uniaxial Compression  
C-Creep Test
2. Sample Preparation and Test Methods

2.1 Quasi-static triaxial compression tests

The extracted core (Figure 1) from Cavern Well (CW) No. 1, Tioga site was prepared in the form of right circular cylinders with nominal dimensions of 1.9 inch in diameter and 4 inch in length for dolomite and 4 inch in diameter and 8 inch in length for rock salt. The dimensions fall within the range of length-to-diameter ratio (2 to 2.5) recommended in ASTM D4543 (“Standard Practice for Preparing Rock Core Specimens and Determining Dimensional and Shape Tolerances”). The ends of the specimen were ground flat within $10^{-3}$ inch tolerance. Samples were visually inspected for significant flaws and general straightness of circumferential surfaces.

Figure 1. Extracted dolomite (left) and rock salt (right) cores from Cavern Well No.1, Tioga site.

Two axial strain gages were mounted on opposite sides of the specimen (180° apart) at mid-height and two circumferential gages were mounted at mid-height around the circumference perpendicular to the longitudinal axis of the specimen. Figure 2 shows the dolomite specimen instrumented with strain gages. The instrumented specimen was placed between upper and lower cylindrical end-caps with the same diameter as the rock specimen.
Then, the specimen assembly was coated with approximately 1/16 inch thick impervious polyurethane membrane (see Figure 2). To maintain uniform thickness of the membrane during curing the specimen assembly was turned on a lathe along the axial centerline of the assembly. The flexible membrane allowed the confining pressure to be applied hydrostatically on the specimen and at the same time prevents the confining fluid from infiltrating into the specimen.

After the flexible membrane was cured the instrumented specimen assembly was placed in a triaxial pressure vessel capable of operating at confining pressures up to 70,000 psi. The vessel was also equipped with 12 coaxial feed-throughs for transmitting data from the strain gages to the data acquisition system. Triaxial compression tests were conducted in a 1 million lb. servo-controlled loading machine shown in Figure 3. After the specimen assembly was placed in the pressure vessel, hydraulic pressure was applied to a prescribed level of confining pressure, P. Table 2 shows the prescribed level of confining pressure for each test. The servo-controlled system controlled hydrostatic pressure \((\sigma_1=\sigma_2=\sigma_3=P\) where \(\sigma_1, \sigma_2,\) and \(\sigma_3\) are the maximum, intermediate, and minimum principal stresses, respectively\). After the confining pressure, P, was stabilized, the specimen was loaded axially at a constant displacement rate of \(4\times10^{-5}\) inch/s which corresponds to a strain rate of \(10^{-5}/s\). During testing, seven channels of data including time, axial load, axial stroke, axial strains from gages, and lateral strains from two gages, were recorded using a DATAVG-event triggered data acquisition program (Hardy, 1993). The experimental apparatus used for the compression tests meets or exceeds the requirements of ASTM2664 for the triaxial compression tests.

For dolomite specimens, the axial load was increased until the peak load, \(P_p\), was reached. The compressive strength of the rocks was calculated from

\[C_o=P_p/\pi r^2\]
where $C_o$ is the compressive strength of the rock in psi; $P_p$ is the peak load in lbs.; and $r$ is the radius of the specimen in inches.

The two fundamental properties to describe the stress-strain behavior of the rock are the Young’s modulus, $E$, and Poisson’s ratio, $\nu$. The proportional constant between stress and strain in the elastic portion of compression tests defines the Young’s modulus:

$$E = \frac{\sigma_a}{\varepsilon_a}$$

where $\sigma_a$ is the axial stress and $\varepsilon_a$ is the axial strain. The Young’s modulus was determined using least square fits of a straight line (or linear regression analysis) to the stress strain data ranging in the interval from 10 to 50% of the peak stress. When approximately 50% of the expected peak load, $P_p$, was reached, unloading and reloading cycles were carried out. Reversibility of deformation was usually observed during unloading and reloading cycles if the stress level was below the yield stress. Therefore, we may calculate the modulus of elasticity due only to the elastic deformation of the specimen from the slope of the unloading curves. Linear regression analysis was also used to obtain the best-fit straight line to the unloading curve.

The other important elastic constant is the Poisson’s ratio defined as the ratio between the axial, $\varepsilon_a$, and lateral, $\varepsilon_l$, strains:

$$\nu = \frac{|\varepsilon_l|}{|\varepsilon_a|}$$

Figure 3. Triaxial compression test set-up with 1 million lb. load frame and 70,000 psi pressure vessel.
When the rock is loaded it initially compresses elastically (plastic strains do not affect the volume of the rock). As deviatoric stress is further incremented, for some stress states, microfracturing becomes prominent and the volumetric strain deviates from elastic compression. In fact, the rock volume will increase under certain stress conditions. The onset of dilatancy can be defined in several ways, however, for consistency with the literature (Mellezard and Pfeifle, 1994), it will be defined as the point at which the rock reaches its minimum volume (or dilation limit). The stress state corresponding to the dilation limit can be described by two stress invariants: $I_1$, the first invariant of the Cauchy stress tensor, and $J_2$, the second invariant of the deviatoric stress tensor. In terms of the principal stresses the two invariants are defined as follows:

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3$$
$$J_2 = \frac{1}{6} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]$$

where $\sigma_1$, $\sigma_2$ and $\sigma_3$ are the maximum, intermediate, and minimum principal stresses, respectively.

### 2.2 Steady-state triaxial creep tests

In order to determine the time-dependent deformation of the rock salt from the Tioga field, five creep tests were conducted using the Sandia creep machine shown in Figure 4. As in the triaxial compression test, a right circular cylindrical specimen (4 inch in diameter and 8 inch in length nominally) was prepared according to ASTM D4543. Two strain gages were mounted along the longitudinal axis of the specimen 180° apart. The specimen was placed between the cylindrical end-caps and encapsulated in an impermeable viton jacket. Figure 5 shows the A1MH01 rock salt specimen before and after the jacket is applied.

First, the specimen assembly was placed in the pressure vessel and was loaded to a hydrostatic pressure equal to the confining pressure. After the confining pressure is stabilized, the specimen was heated in the pressure vessel to a prescribed level. The predetermined levels of confining pressure and the temperature for each specimen are shown in Table 2. Finally, the axial stress was increased to create the stress condition with constant confining pressure and prescribed axial stress difference. Axial strains are measured by two axial strain gages. As a back up, a linear displacement transducer (LVDT) was mounted to measure the axial displacement of the piston as it enters the pressure vessel. The deformation measured by the LVDT consists of displacements from both the specimen and the steel end-caps. The test conditions (confining pressure, axial stress difference, and specimen temperature) were maintained throughout the duration of the test.

The response surface of the strain rate over the space of stress and temperature is based on the following empirical power law (Dorn, 1957): 

$$\dot{\varepsilon} = C\sigma^n \exp\left(-\frac{Q}{RT}\right)$$
where \( \dot{\varepsilon}_s \) = Steady state strain rate  
\( C \) = Constant  
\( \sigma \) = Applied axial stress difference in psi  
\( n \) = Stress exponent  
\( Q \) = Activation energy  
\( R \) = Gas constant  
\( T \) = Temperature in Kelvin

To determine the response surface defined by three unknown parameters of this equation, \( C, n \) and \( Q/R \), the steady state strain rate must be determined for each test stage.

Figure 4. Sandia National Laboratories creep machine.
3. Laboratory Test Results

3.1 Compressive strengths and elastic constants

Twelve dolomite and twelve rock salt specimens from Cavern Well No. 1, Tioga field were tested to obtain elastic constants, $E$ and $\nu$, and damage criteria. Figure 6 shows the failed dolomite specimens retrieved after reaching a peak load. Dolomite specimens failed under confining pressure showed a well-defined single shear failure surface whereas specimens fractured under uniaxial compression showed multiple splitting fractures parallel to the longitudinal axis of the specimen.

Figure 7 shows rock salt specimens retrieved after uniaxial and triaxial compression tests. Unlike the brittle failure shown in dolomite specimens, the rock salt specimens exhibited strain hardening ductile deformation without reaching the peak load associated with the brittle failure of the specimen even after undergoing more than 3 % strain. Stress vs. strain plots for all triaxial compression tests are given in Appendices B (dolomite) and C (rock salt) and the results are summarized in Table 2.

Unconfined compressive strength of the dolomite is determined to be approximately 15,100 psi and the strength increases as the confining pressure increases. The Young’s modulus of dolomite was determined to be $6.4 \times 10^6$ psi, with a Poisson’s ratio of 0.26 ($\pm 0.04$). The Young’s modulus of rock salt was determined to be $2.4 \times 10^6$ psi, with a Poisson’s ratio of 0.34 ($\pm 0.23$). The large standard deviation is a result from two unconfined compression tests shown in Table 2. If we consider these two results as outliers, then the average Poisson’s ratio becomes 0.24 ($\pm 0.07$).
To obtain the elastic Young’s modulus, $E_{\text{elastic}}$, of the rock, we conducted unloading and reloading cycles during the compression tests. Figures 8 through 10 show examples of unloading and reloading cycles. We calculated the $E_{\text{elastic}}$ from the slope of the unloading curve. Table 2 and Figure 9 shows the modulus of elasticity due only to the elastic deformation of the specimen.

The elastic Young’s modulus was approximately as $7.8 \pm 0.9 \times 10^6$ psi for dolomite and $5.0 \pm 0.5 \times 10^6$ psi for rock salt, respectively. For the dolomite, $E_{\text{elastic}}$ was approximately 20% higher than $E$ determined from the slope of the virgin loading curve. For the rock salt, $E_{\text{elastic}}$ was approximately twice as large as $E$, suggesting that a large portion of deformation for the rock salt is not reversible.

Figure 6. Dolomite specimens retrieved after reaching a peak load in the uniaxial (MHP-DT11) and triaxial compression (MHP-DT12) tests. The nominal diameter of the specimen was 1.9 inches.

Figure 7. Rock salt specimens retrieved after uniaxial (MHP-ST11) and triaxial compression (MHP-ST8) tests. The specimen did not show failure surfaces after undergoing more than 3% strain. The nominal diameter of the specimen was 4 inches.
Figure 8. Stress-strain plot obtained during the triaxial compression test for the MHP-DT6 dolomite. The volumetric strain was calculated from the axial and lateral strains. Also shown are the components for elastic constants (Young’s modulus $E$ and Poisson’s ratio $\nu = |\varepsilon_l|/|\varepsilon_a|$). See Appendix B for other test records.
Figure 9. Unloading and reloading portion of the stress-strain plot obtained during the triaxial compression test of the MHP-DT6 dolomite. The elastic portion of the Young’s modulus, $E_{\text{elastic}}$, was calculated from the slope of the unloading and reloading curves.
Figure 10. Stress-strain plot obtained during the triaxial compression test of the MHP-ST1 rock salt. The volumetric strain was calculated from the axial and lateral strains. See Appendix C for other test records.
Figure 11. Unloading and reloading portion of the stress-strain plot obtained during triaxial compression test of the MHP-ST1 rock salt. The dilation limit is shown as $\sigma_{a,d}$ in which the volume of the sample reaches the minimum point. The elastic portion of the Young’s modulus, $E_{\text{elastic}}$, was calculated from the slope of the unloading and reloading curves.
<table>
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<tr>
<th>Specimen no.</th>
<th>Rock type</th>
<th>Sample interval (ft)</th>
<th>Sample diameter (in)</th>
<th>Sample length (in)</th>
<th>P (psi)</th>
<th>$E_{\text{elastic}}$ (psi $\times 10^6$)</th>
<th>E (psi $\times 10^6$)</th>
<th>$\nu$</th>
<th>$\sigma_{a,p}$ (psi)</th>
<th>$\sigma_{a,d}$ (psi)</th>
<th>$I_1$ (psi)</th>
<th>$J_2^{0.5}$ (psi)</th>
<th>$I_1$ (psi)</th>
<th>$J_2^{0.5}$ (psi)</th>
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<td>6.61</td>
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$I_1 = \sigma_1 + 2P$

$P = \sigma_2 = \sigma_3 =$ confining pressure

$\sigma_{a,p}$ - peak stress level for failure (psi)

$\nu$ (Poisson's ratio) = $|e_1|/|e_a|$

$\sigma_{a,d}$ – stress for dilation limit (psi)

$E$ (Young's Modulus) = $\sigma_a / \epsilon_a$ (psi)

$E_{\text{elastic}}$ - elastic Young's modulus obtained from the slope of the unloading curve (psi).

$I_1 = \sigma_1 + 2P$

$J_2^{0.5} = (\sigma_a - P)^2 / 3^{0.5}$
3.2 Damage Criteria in the triaxial compression tests

For purposes of interpreting the results a criterion is needed to evaluate the adequacy of the rock for the storage cavern. In triaxial compression tests, where the axial stress was the major principal stress, $\sigma_1$, and the confining pressure $P$ was as $\sigma_2$ and $\sigma_3$, the mean stress invariant, $I_1$, and the square root of the deviator invariant, $J_2$, can be described as,

$$I_1 = \sigma_1 + 2P$$

$$J_2^{0.5} = \left(\frac{(\sigma_1 - P)^2}{3}\right)^{0.5}$$

The values of $I_1$ and $J_2^{0.5}$ for different confining pressures are listed in Table 2. During the shear failure of the specimens, the state of stress can be represented as a shear failure envelope represented empirically by the linear equation.

$$J_2^{0.5} = A + BI_1$$

where $A$ and $B$ are unknown parameters to be determined for different rock types.

We used a linear regression analysis to determine the unknown parameters that minimized the sum of the squares of errors between the model, predicted values and the observed $J_2^{0.5}$ values for different confining pressures. The damage criterion based on the peak stress of the dolomite was represented in terms of invariants:

$$J_2^{0.5} \text{(psi)} = 3113 + 0.34 I_1 \text{(psi)}$$

Unlike the brittle failure in dolomite, the rock salt specimens deformed in ductile fashion without the peak stress and significant stress drop immediately following the peak stress. The volumetric strain ($\Delta V/V = \varepsilon_a + 2\varepsilon_l$) was calculated and shown on each plot. Based on the volumetric strain data, dilatancy (volume increase of the specimen due to the creation of new cracks in the specimen) in the triaxial compression tests was observed and considered to be the damage stress for rock salt. As in the dolomite the damage criterion of the rock salt was represented in terms of invariants:

$$J_2^{0.5} \text{(psi)} = 704 + 0.17 I_1 \text{(psi)}$$

If we apply the same dilation limit criterion to dolomite, we conservatively estimate the following damage criterion:

$$J_2^{0.5} \text{(psi)} = 2614 + 0.30 I_1 \text{(psi)}$$

Figures 12 and 13 summarize the damage criteria obtained for the dolomite and the rock salt.
The figures show that a sufficient number of quasi-static tests have been performed to characterize the damage criteria of Tioga dolomite and rock salt. Also included are previous results from Tioga Well 501 (TW-501).

Figure 12. Damage criteria determined by the linear regression analysis of the triaxial compression data for Tioga dolomite (CW-Cavern Well, TW-Tioga Well).
Figure 13. Damage criterion determined by the linear regression analysis of the triaxial compression data for Tioga rock salt.

\[ J_{2}^{0.5} = 704 + 0.17 I_{1} \]
3.3 Creep Parameters

As shown in Table 3 and Figure 14, the test matrix for steady-state triaxial creep tests was designed to obtain the response surface of strain rate dependency on stress and temperature systematically. As shown in section 2.2 the strain rate was described by three unknown parameters C, n, and Q/R over the space defined by two independent variables of stress difference ($\sigma_1 - \sigma_3$) and T. A typical controlled test condition is shown in Figure 15. See Appendix D for other test conditions.

![Figure 14. Schematic of an experimental design to obtain the response surface defined by three unknown parameters and two independent variables ($\sigma_1 - \sigma_3$ and T) with two levels.](image)

The data obtained from these tests include the steady-state creep rate corresponding to a particular state of stress and a temperature (Figure 16). The test condition was maintained by a feedback system throughout the duration of testing. All tests were performed approximately at 2180 psi confining pressure. Under this test environment we obtained creep data consisting of axial strain vs. time plot. From this plot the strain rate was calculated by differentiating the strains with respect to time (Figure 17). As suggested by the asymptotic trend near the end of the creep test, the steady-state creep rate was reached after approximately 15 days of creep testing. The test results are summarized in Table 3.

In order to determine the creep parameters (C, n, and Q/R) a 'nonlinear regression' technique was used (Appendix E). Nonlinear regression analysis is a technique for fitting an arbitrary function to a given set of data. The procedure determines the best-fit response surface defined by three unknown parameters of the empirical power law. The regression technique considers the entire database at once to solve for the unknown parameters using an iteration procedure to minimize the sum of squares of the error (Draper and Smith, 1981).
The results of the ‘nonlinear regression’ analysis provide the following relationship for the steady-state strain rate of Tioga rock salt as:

\[ \mathcal{E}_s = 1.2 \cdot 10^{-17} \sigma^{4.75} \exp\left(-\frac{6161}{T}\right) \]

where \( \mathcal{E}_s \) is steady state strain rate in \( \text{s}^{-1} \), \( \sigma \) is applied axial stress difference in psi, and \( T \) is temperature in Kelvin.

![A1MHP01 (Test Condition)]

Figure 15. Controlled test condition (temperature \( T \), axial stress \( \sigma_1 \) and confining pressure \( \sigma_2 = \sigma_3 \)) during steady-state creep testing for the A1MHP01 specimen. See Appendix D for other test records
Figure 16. Strain vs. time plot during steady-state creep testing for the A1MHP01 specimen. See Appendix D for other test records.
Estimated Steady-State Strain Rate

Figure 17. Strain rate vs. time plot to obtain steady-state strain rate for the A1MHP01 specimen. See Appendix D for other test records.
Table 3. Summary of creep tests for Tioga rock salt from Cavern Well No. 1, Pennsylvania.

<table>
<thead>
<tr>
<th>Test I.D.</th>
<th>Depth (ft)</th>
<th>Sample diameter (inch)</th>
<th>Sample length (inch)</th>
<th>Axial stress (psi)</th>
<th>Confining pressure (psi)</th>
<th>Temperature (°F)</th>
<th>Test start date</th>
<th>Test end date</th>
<th>Test duration (day)</th>
<th>Estimated steady-state strain rate (10^{11}/s)</th>
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<td>2175</td>
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<td>8/16/00</td>
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<td>5075</td>
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<td>1562**</td>
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</table>

Estimated steady state strain rates were calculated by averaging the last five daily strain rates.

*Steady state strain rate was calculated by fitting a straight line to the axial strain vs. time data from 10^6 to 4\times10^6 s range of data. The slope of the best-fit straight line was 267\times10^{11}/s.

** Due to the failure of an axial strain gage after 2.5\times10^6 s testing, the steady state strain rate was calculated by fitting a straight line to the axial strain vs. time data from 2\times10^6 to 2.35\times10^6 s data. The slope of the best-fit straight line was 1562\times10^{11}/s.
3.4 Comparison to Previous Test Results

Prior laboratory testing was performed by Sandia National Laboratories (1995) Ecole Nationale Supérieure des mines de Paris (1995) on core taken from Tioga Well 501 (TW-501), located approximately 1.6 miles ENE of Cavern Well No. 1 (CW No. 1). Dilatancy and failure criteria were derived from the testing and used in numerical analyses to evaluate the design and operation of the cavern field (Ehgartner, 1996). The criteria used to define dilatant damage of the salt in 1996 was

\[ J_2^{0.5} \text{ (psi)} = 200 + 0.15 I_1 \text{ (psi)} \]

The dilatant damage criteria for salt tested in this report is

\[ J_2^{0.5} \text{ (psi)} = 704 + 0.17 I_1 \text{ (psi)} \]

Therefore, the salt tested in this report from CW No.1 results in a criteria that is more resistant to damage. Similarly, the criteria used in 1996 to evaluate damage to the non-salt overburden layers was

\[ J_2^{0.5} \text{ (psi)} = 350 + 0.26 I_1 \text{ (psi)} \]

The dilatant damage criteria for non-salt tested in this report is

\[ J_2^{0.5} \text{ (psi)} = 2614 + 0.30 I_1 \text{ (psi)} \]

Therefore, the non-salt rock (dolomite) tested in this report from CW No.1 results in a criteria that is more resistant to damage than measured in the previous analyses.

A comparison of failure criteria for the dolomite also show that the core tested from CW No. 1 is considerably stronger than measured in the 1996 analyses.

A comparison of salt creep rates is shown in Figure 18 using creep relationships derived from the previous and recent tests. The stresses span the entire range of conditions tested, and the strain rates are for temperature conditions at cavern depth (110 °F). The creep rate of salt from CW No. 1 is intermediate to the rates derived from previous testing at Sandia and Ecole Nationale Supérieure des mines de Paris.
Figure 18. Comparison of creep rates from 1995 testing by Sandia and Ecole (Ecole Nationale Superieure des mines de Paris) with results presented in this report.
4. Conclusions

We conducted twenty four triaxial compression and five creep tests to characterize the quasi-static and creep properties of Tioga dolomite and rock salt for the proposed Tioga storage cavern project in Pennsylvania. The results from laboratory experiments can be summarized as follows.

- The Young’s modulus of the dolomite was $6.4 \pm 1.0 \times 10^6$ psi, with a Poisson’s ratio of $0.26 \pm 0.04$. The elastic Young’s modulus obtained from the slope of the unloading and reloading curve was $7.8 \pm 0.9 \times 10^6$ psi.
- The Young’s modulus of the rock salt, which will host the storage cavern, was $2.4 \pm 0.65 \times 10^6$ psi, with a Poisson’s ratio of $0.24 \pm 0.07$. The elastic Young’s modulus was determined to be $5.0 \pm 0.46 \times 10^6$ psi.
- Based on shear failure, the damage criterion for the dolomite is estimated as $J_2^{0.5} (\text{psi}) = 3113 + 0.34 I_1 (\text{psi})$. Whereas based on the dilation limit the criterion is conservatively estimated as $J_2^{0.5} (\text{psi}) = 2614 + 0.30 I_1 (\text{psi})$.
- Based on dilation limit, the damage criterion for the rock salt is estimated as $J_2^{0.5} (\text{psi}) = 704 + 0.17 I_1 (\text{psi})$.
- The creep deformation of the Tioga rock salt was modeled as $\dot{e}_s = 1.2 \cdot 10^{-17} \sigma^{4.75} \exp (-6161/T)$, where $\dot{e}_s$ is the steady state strain rate in $\text{s}^{-1}$, $\sigma$ is the applied axial stress difference in psi, and $T$ is the temperature in Kelvin.

In comparison to previous test results and criteria used to evaluate the performance and impact of the planned cavern field on the overlying stratigraphy, the rock salt tested in this report (from CW No. 1) has creep characteristics intermediate to previous test results on core from a nearby Tioga Well -501. The measurements presented in this report suggest the rock salt and dolomite have a greater resistance to damage than previously measured or inferred from TW-501.
References


Appendix A

Geologic log of selected sections of CW No. 1 hole used for triaxial compression and steady-state creep tests.
<table>
<thead>
<tr>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Explanation of Graphic Geologic Log</strong></td>
</tr>
</tbody>
</table>

**Descriptive Geology**

- **Carbonate rock**: dolomite, limestone; may be organic-rich
- **Shale**: fissile shale to claystone or mudstone; color may also represent wisps or laminae
- **Halite**: rock salt, with or without impurities; may include minor unidentified evaporite minerals

**Measured depth of start or end of cored interval; depths measured from even 1-foot depths marked on core**

**Approximate diameter of core and extent of cored interval**

**Graphical representation of relative variation in content of anhydrite**: (in evaporite units only); most accurate over short or continuous core intervals

**Graphical representation of relative variation in content of large, clear halite crystals**: (in evaporite units only); most accurate over short or continuous core intervals

**Graphical representation of relative variation in “typical” size of halite crystals, both clear and “black”**: (in evaporite units only); most accurate over short or continuous core intervals

**Anhydrite(?):** bedded, nodules, masses, and veinlets; line width is roughly proportional to size, thickness, volume, etc.; spacing of symbols is roughly proportional to density or frequency of occurrence.

**Graphical representation of fracture(s) with measured angle(s)** to core axes (C.A.): angle is drawn roughly proportional to actual angle to C.A.; roughness or prominence of fracture approximately represented.

**Sample interval and test identification**

**Avg Core Recovery Hole**

<table>
<thead>
<tr>
<th>% Core Recovered</th>
<th>Core Size</th>
<th>ROD</th>
<th>Sample Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Dolomite(?) -- essentially as above.

No Core
No Core

Evaporite Unit — Clear to black halite crystals to 1-2 cm; bottom of core segment is massive halite x < 10 cm core diameter. There is a weak but definite "foliation" to rock ~60-60 C.A. Anhydrite(?) nodules, masses, and weakly defined stringers ~60-60 C.A.; most anhydrite(?) 0.5 cm to 1.2 cm.

No Core

Evaporite Unit — Clear to black halite crystals, as above.

Anhydrite(?) nodules and masses interstitial to crystalline halite; typically ~0.5 cm; larger masses ~1 cm above ~599.2 ft.

No Core

Depth scale omits 3 feet from previous page

Evaporite Unit — Clear to black halite crystals to 1-2 cm; bottom of core segment is massive halite x < 10 cm core diameter. There is a weak but definite "foliation" to rock ~60-60 C.A. Anhydrite(?) nodules, masses, and weakly defined stringers ~60-60 C.A.; most anhydrite(?) 0.5 cm to 1.2 cm.

No Core

Evaporite Unit — Clear to black halite crystals, as above.

Anhydrite(?) nodules and masses interstitial to crystalline halite; typically ~0.5 cm; larger masses ~1 cm above ~599.2 ft.

No Core

Depth scale omits 3 feet from previous page
Evaporite Unit – continued

anhydrite(?) nodules < 0.5 cm

78.4-79.0 Intv. of apparent core loss

fract. in transit (?)

fract. in transit (?)

anhydrite(?) nodules < 0.5 cm

82.9-83.25 Intv. of apparent core loss

No Core
Appendix B

Stress-strain plots for Tioga dolomite obtained during the triaxial compression tests for the MHP project. Shown are the axial, lateral and calculated volumetric strains, respectively.

- $\varepsilon_a$ – axial strain (right or red line)
- $\varepsilon_l$ – lateral strain (left or blue line)
- $\varepsilon_v$ – volumetric strain (middle or green line)

Structure of the file name or the title of the plot
- MHP-DT1 to 12 (MHP, Tioga, Dolomite, Triaxial compression #)
- # = sample number
MHP-DT1

$\sigma_a - P$ (psi)

Strain

$P = 1450$ psi
MHP-DT2

\( \sigma_a - P \) (psi)

\( \varepsilon_l \)

\( \varepsilon_v \)

\( \varepsilon_a \)

Strain

P=1454 psi
MHP-DT6

Strain

\( P = 727 \text{ psi} \)

\( \varepsilon \)

\( \varepsilon_l \)

\( \varepsilon_v \)

\( \varepsilon_a \)
MHP-DT7

\( \sigma_a - P \) (psi) vs Strain

\( \epsilon_a \), \( \epsilon_v \), and \( \epsilon_l \)

P = 2901 psi
MHP-DT8

\[ \sigma_a - P \text{ (psi)} \]

\[ \epsilon_l \quad \epsilon_v \quad \epsilon_a \]

\[ P = 290 \text{ psi} \]

\[ \text{Strain} \]
Appendix C

Stress-strain plots for Tioga rock salt obtained during the triaxial compression tests for the MHP project. Shown are the axial, lateral and calculated volumetric strains, respectively.

\[ \varepsilon_a \] – axial strain (right or red line)
\[ \varepsilon_l \] – lateral strain (left or blue line)
\[ \varepsilon_v \] – volumetric strain (middle or green line)

Structure of the file name or the title of the plot

- MHP-ST1 to 12 (MHP, Tioga, Rock Salt, Triaxial compression #)
- # = sample number
MHP-ST1

\[ \sigma_a - P \text{ (psi)} \]

\[ \varepsilon_l, \varepsilon_v, \varepsilon_a \]

\[ P = 1460 \text{ psi} \]
MHP-ST2

strain - stress relationship

\[ \sigma_a - P \text{ (psi)} \]

\[ \varepsilon_l \]

\[ \varepsilon_v \]

\[ \varepsilon_a \]

P = 2160 psi
MHP-ST3

Strain

\[ \sigma - P \text{ (psi)} \]

\[ \varepsilon \]

\[ \varepsilon_l \]

\[ \varepsilon_v \]

\[ \varepsilon_a \]

P=730 psi
MHP-ST4

\[ \sigma_a - P \text{ (psi)} \]

\[ \varepsilon_l \]

\[ \varepsilon_v \]

\[ \varepsilon_a \]

P = 1450 psi

Strain
MHP-ST9

$\sigma_a - P$ (psi)

Strain

$P = 310$ psi
MHP-ST10

\[ \sigma_a - P \text{ (psi)} \]

Strain

\[ P = 2900 \text{ psi} \]
Appendix D

Test conditions, Strain vs. Time, and Strain-rate vs. Time plots for Tioga rock salt obtained during the steady-state triaxial creep tests for the MHP project.

\[ \varepsilon_a \] – axial strain (right or red line)
\[ \varepsilon_l \] – lateral strain (left or blue line)
\[ \varepsilon_v \] – volumetric strain (middle or green line)

Structure of the file name or the title of the plot

- A*MHP0# (*-creep apparatus I.D, #-sample number)
Temperature (°F) vs. Time (s) for A1MHP01 (Test Condition)

- Temperature range: 0°C to 80°C
- Time range: 10^6 s

Stress conditions:
- \(\sigma_1\) and \(\sigma_2 = \sigma_3\)

Graph shows the relationship between temperature and time, with stresses plotted as \(\sigma_1\) and \(\sigma_2 = \sigma_3\) constant over time.
A1MHP01 (Strain)

Axial Strain (Δl/l)

σ₁ = 3625 psi
σ₂ = σ₃ = 2175 psi
T = 78°F
Axial Strain Rate (x10^{-11}/s)

\[ \sigma_1 = 3625 \text{ psi} \]
\[ \sigma_2 = \sigma_3 = 2175 \text{ psi} \]
\[ T = 78^\circ \text{F} \]
A2MHP02 (Test Condition)

Temperature (°F)

Stresses (psi)

\[ \sigma_2 = \sigma_3 \]
\[ \sigma_1 = 3625 \text{ psi} \]
\[ \sigma_2 = \sigma_3 = 2175 \text{ psi} \]
\[ T = 194^\circ \text{F} \]
$\sigma_1 = 3625 \text{ psi}$

$\sigma_2 = \sigma_3 = 2175 \text{ psi}$

$T = 194^\circ\text{F}$
A2MHP02 (Fitted strain-rate)

\[ y = -0.00017313 + 2.6694 \times 10^{-9}x \]

R = 0.99921

Axial Strain (\(\Delta l/l\))

Time (s)

\(\sigma_1 = 3625 \text{ psi}\)

\(\sigma_2 = \sigma_3 = 2175 \text{ psi}\)

T = 194°F
A3MHP03 (Test Condition)

Temperature (°F) vs. Time (s) with Stresses (psi)

\[ \sigma_1 \]

\[ \sigma_2 = \sigma_3 \]
A3MHP03 (Strain)

Axial Strain ($\Delta l/l$) vs. Time (s)

$\sigma_1 = 5075$ psi

$\sigma_2 = \sigma_3 = 2175$ psi

$T = 73^\circ F$
\( \sigma_1 = 5075 \text{ psi} \)

\( \sigma_2 = \sigma_3 = 2175 \text{ psi} \)

\( T = 73^\circ \text{F} \)
Axial Strain ($\Delta l/l$)

$\sigma_1 = 5075 \text{ psi}$

$\sigma_2 = \sigma_3 = 2175 \text{ psi}$

$T = 196^\circ\text{F}$

Time (s)
$\sigma_1 = 5075 \text{ psi}$

$\sigma_2 = \sigma_3 = 2175 \text{ psi}$

$T = 196^{\circ} \text{F}$
Axial Strain ($\Delta l/l$) vs. Time (s)

- $\sigma_1 = 5075$ psi
- $\sigma_2 = \sigma_3 = 2175$ psi
- $T = 196^\circ F$

The fitted strain-rate equation is:

$$y = 0.018017 + 1.562 \times 10^{-8}x$$

with a correlation coefficient $R = 0.99986$. 

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Axial Strain ($\Delta l/l$)

- $\sigma_1 = 4350$ psi
- $\sigma_2 = \sigma_3 = 2175$ psi
- $T = 135^\circ F$
Axial Strain Rate (x10^{-11}/s)

Time (day)

\sigma_1 = 4350 \text{ psi}
\sigma_2 = \sigma_3 = 2175 \text{ psi}
T = 135^\circ \text{F}
Appendix E

Nonlinear regression analysis applied to the estimation of creep parameters.
We used a 'nonlinear regression analysis' which determines the best-fit response surface defined by three unknown parameters of the empirical power law. Nonlinear regression analysis is a technique for fitting an arbitrary function to a given set of data point. For the power law creep model, the arbitrary function is expressed as:

\[ Y = P_1 (X_1^{P_2}) \exp(P_3/X_2) + \varepsilon \]

where \( P_1, P_2, \) and \( P_3 \) are the three unknown parameters; \( X_1 \) and \( X_2 \) are the two independent variables; \( Y \) is the dependent variable (or response); and \( \varepsilon \) is the random error. Provided that we have \( m (>3) \) sets of data points, \((X_{1i}, X_{2i}, Y_i), (X_{12}, X_{22}, Y_2), \ldots, (X_{1m}, X_{2m}, Y_m)\), the optimum values of the unknown parameters \( P_j \) \((j=1 \text{ to } 3)\) can be estimated by minimizing the sum of squares of errors.

\[ SSE = \varepsilon^2 = \sum_{i=1}^{m} \left( Y_i - P_1 (X_{1i}^{P_2}) \exp(P_3/X_{2i}) \right)^2 \]

where \( SSE \) is the sum of squares of the random errors between the measured response value \( Y_i \) \((i=1 \text{ to } m)\) and their model-predicted values for all of the \( m \) data points. The least squares solutions for \( P_j \) are found when \( SSE \) is minimum. In order to determine the minimum of \( SSE \) the derivative of \( SSE \) is taken with respect to each \( P_j \). This yields a set of so-called 'normal equations':

\begin{align*}
DF1 &= (X_1^{P_2}) \exp(P_3/X_2) \\
DF2 &= P_1 (X_1^{P_2}) \exp(P_3/X_2) \ln(\text{STRESS}) \\
DF3 &= P_1/X_2 (X_1^{P_2}) \exp(P_3/X_2)
\end{align*}

In the nonlinear regression model, the partial derivative of the model function with respect to the unknown parameters is also represented as a function of the unknown parameters \( P_j \). Therefore, a closed form solution generally does not exist in the nonlinear case. Thus, an iteration procedure is introduced to solve 'normal equations' until the sum of squares of errors is minimized (Draper and Smith, 1981). The following is the listing of BMDP 3R statistical routine to solve the nonlinear model used for the Tioga rock salt:

```
/PROBLEM TITLE IS 'NLRA-CREEP'.
/INPUT VARIABLES ARE 3.
  FORMAT IS FREE.
  FILE IS 'data'.
/VARIABLE NAMES ARE SRATE,STRESS,TEMP.
/REGRESS DEPENDENT IS SRATE.
  PARAMETERS ARE 3.
/PARAMETER INITIALS ARE 10000,5.0,-6000.0.
/FUNCTION F=P1*(STRESS**P2)*EXP(P3/TEMP).
  DF1=(STRESS**P2)*EXP(P3/TEMP).
  DF2=P1*(STRESS**P2)*EXP(P3/TEMP)*LN(STRESS).
  DF3=P1/X2*(STRESS**P2)*EXP(P3/TEMP).
```
DF3=P1/TEMP*(STRESS**P2)*EXP(P3/TEMP).
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