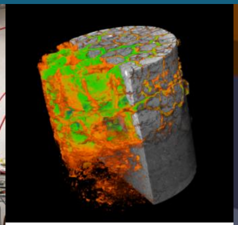
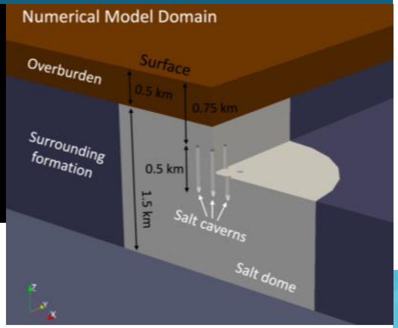
SAND2024-14913C

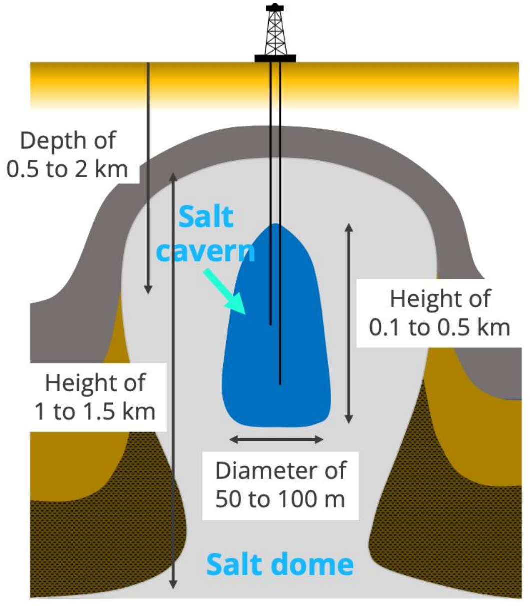
CouFrac 2024

Sandia National Laboratories

Cyclic loading-unloading impacts on geomechanical behaviors of multiple salt caverns for underground hydrogen storage







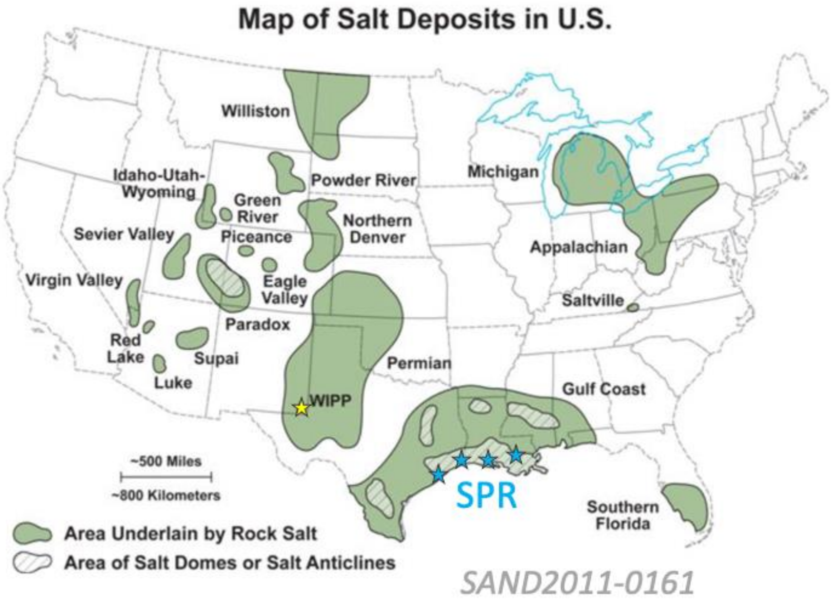
PI: Kyung Won (K-Won) Chang
Team: Benjamin Reedlunn, R. Charles Choens, Tonya S.A. Ross, Anna S. Lord
University partner: Texas A&M University, USA

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Motivation

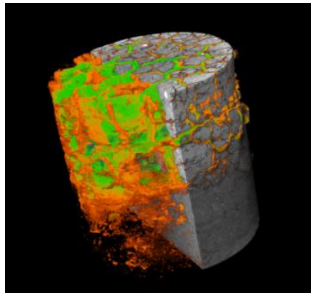
- Underground caverns in salt formations are a promising approach to store hydrogen (H_2) because of salt's extremely low permeability and self-healing behavior.

  In the United States, salt domes are potential targets because of their storage volumes, as well as their proximity to critical markets and infrastructure



- However, there is still a gap in research by the salt cavern storage community to understand the geomechanical behaviors of salt driven by frequent operation cycles of H_2 injection-production, which may significantly impact the cost-effective storage-recovery performance.

Workflow of Geomechanical Analysis



Material constitutive model
Viscoplastic behavior of salt

Geomechanical lab test
Parameters for constitutive model

Geometric information
Cavern (sonar data)
Dome (seismic/borehole data)

Operation state
Well head pressure
Fluid interface depth, if needed

Cavern volume calculation

Subsidence survey
InSAR/GPS

Geomechanical simulation
Sierra/SolidMechanics runs in SNL's High-Performance Computing platform

Model calibration
Setup of subroutine for Sierra/SM
Operating pressure within caverns

Geomechanical analysis
Evaluation of structural stability of cavern/dome for current and future operations

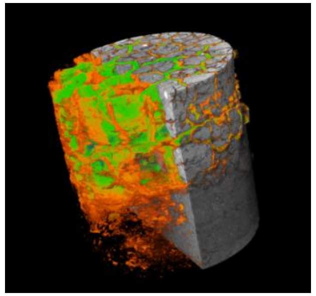
Evaluation of drawdown limits for individual caverns

Analysis of cause and potential of wellbore damage

Providing desirable operating guidelines based on geomechanical stability of cavern/dome

Geophysical survey
Microseismic monitoring
DAS/Fiber

Workflow of Geomechanical Analysis



Material constitutive model
Viscoplastic behavior of salt

Geomechanical lab test
Parameters for constitutive model

Geometric information
Cavern (sonar data)
Dome (seismic/borehole data)

Operation state
Well head pressure
Fluid interface depth, if needed

Cavern volume calculation

Subsidence survey
InSAR/GPS

Geomechanical simulation
Sierra/SolidMechanics runs in SNL's High-Performance Computing platform

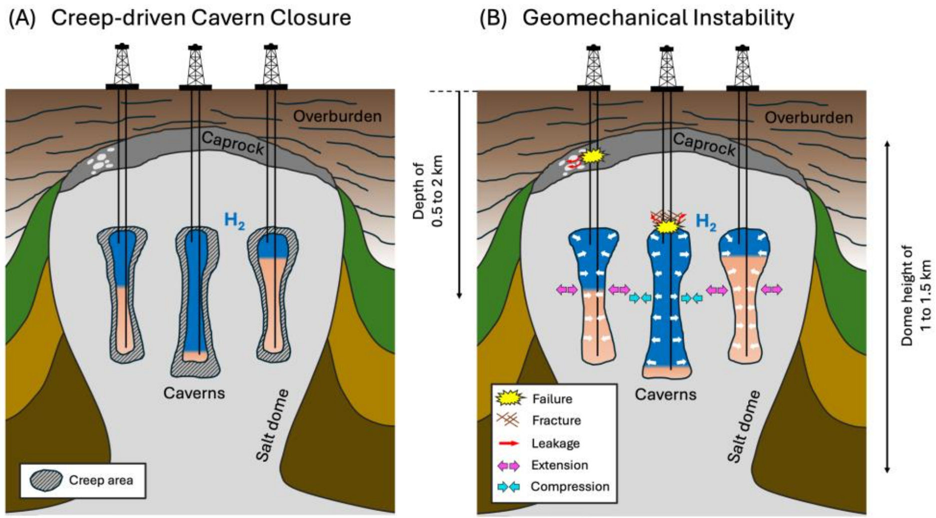
Model calibration
Setup of subroutine for Sierra/SM
Operating pressure within caverns

Geomechanical analysis
Evaluation of structural stability of cavern/dome for current and future operations

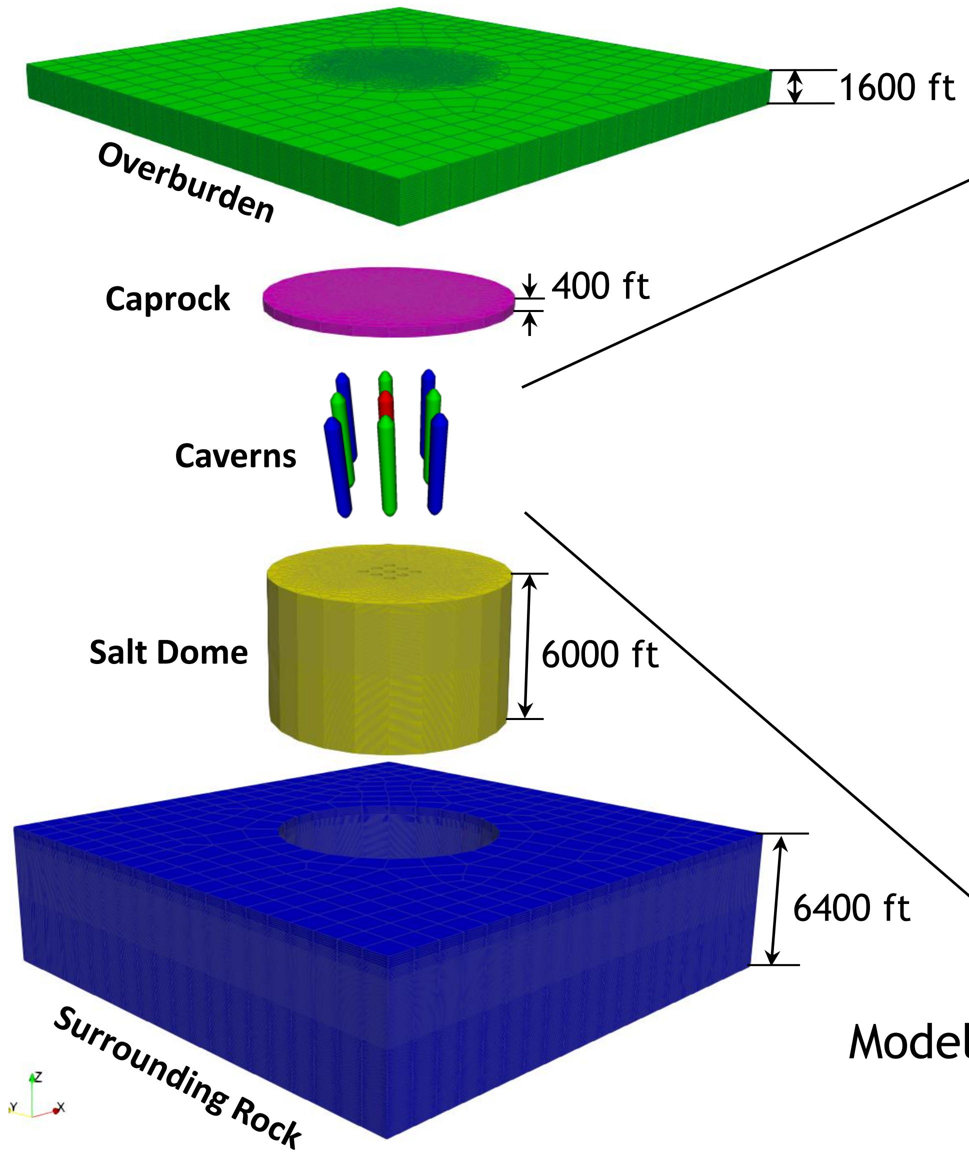
Evaluation of drawdown limits for individual caverns

Analysis of cause and potential of wellbore damage

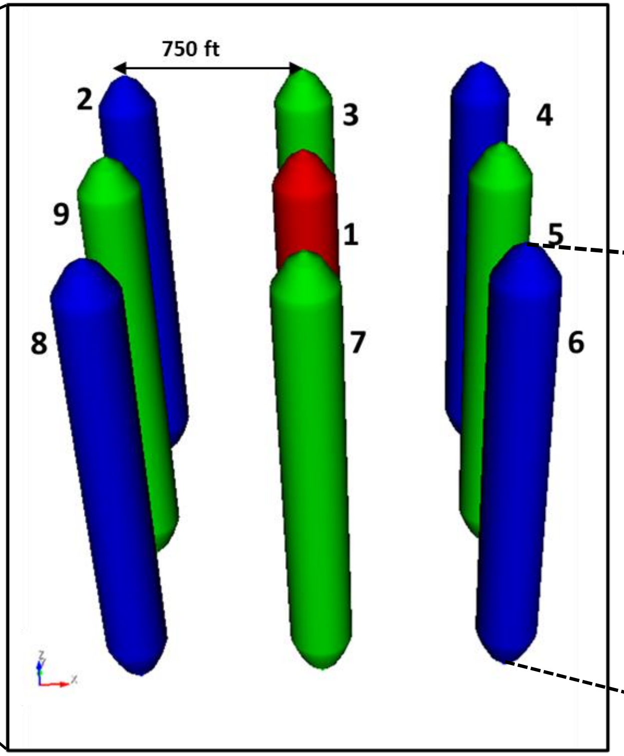
Providing desirable operating guidelines based on geomechanical stability of cavern/dome



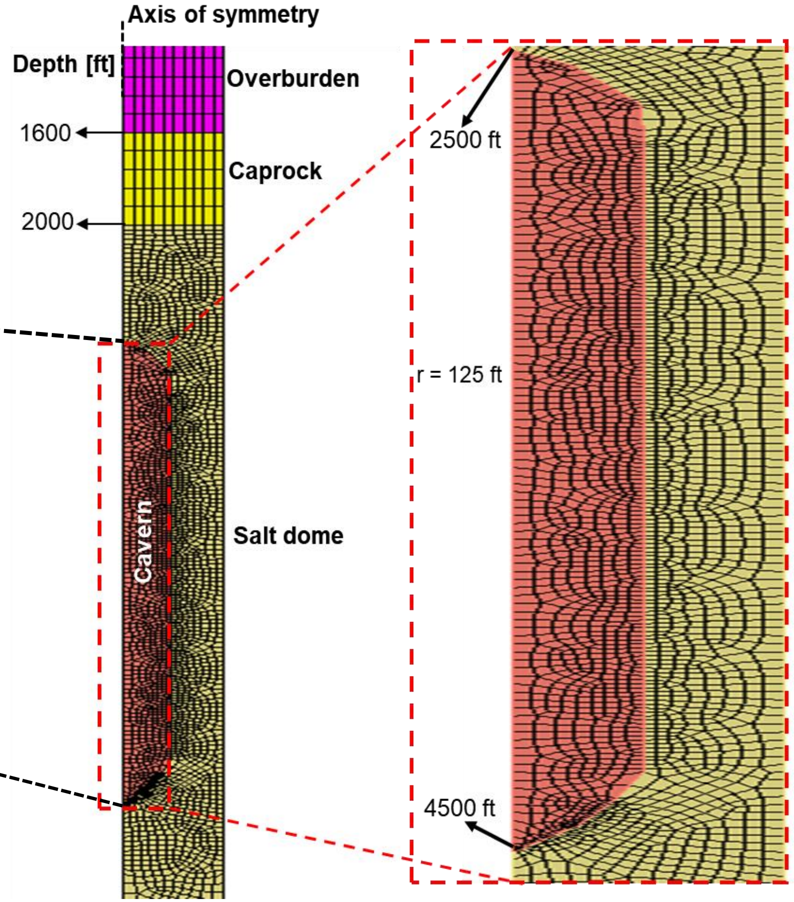
Generic Multi-Cavern Model Setup



1000 ft ≈ 0.3 km



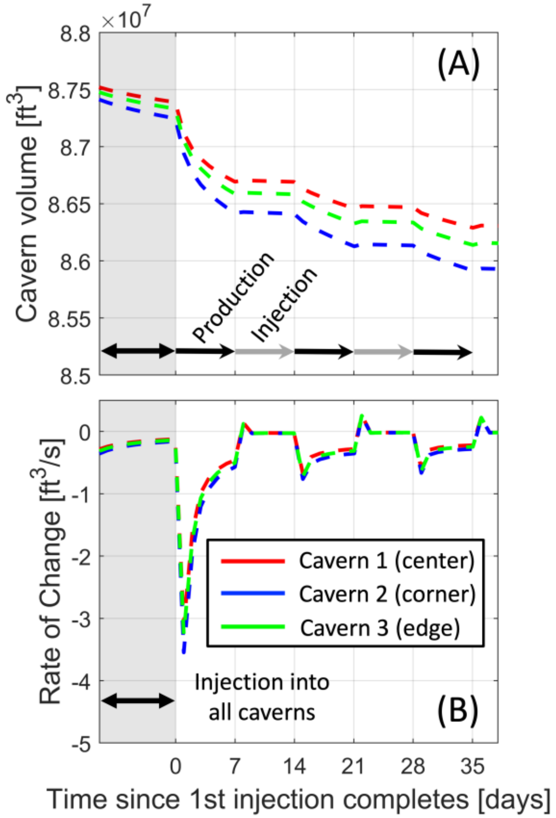
Model geometry

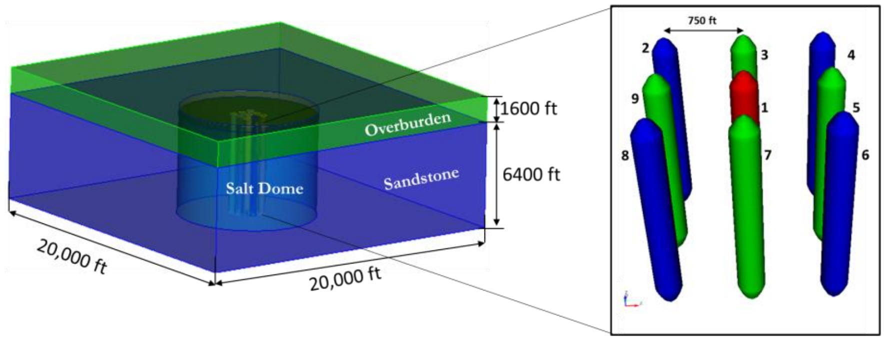


Numerical mesh

Result: CASE 1 – Unloading Impact

Cavern closure



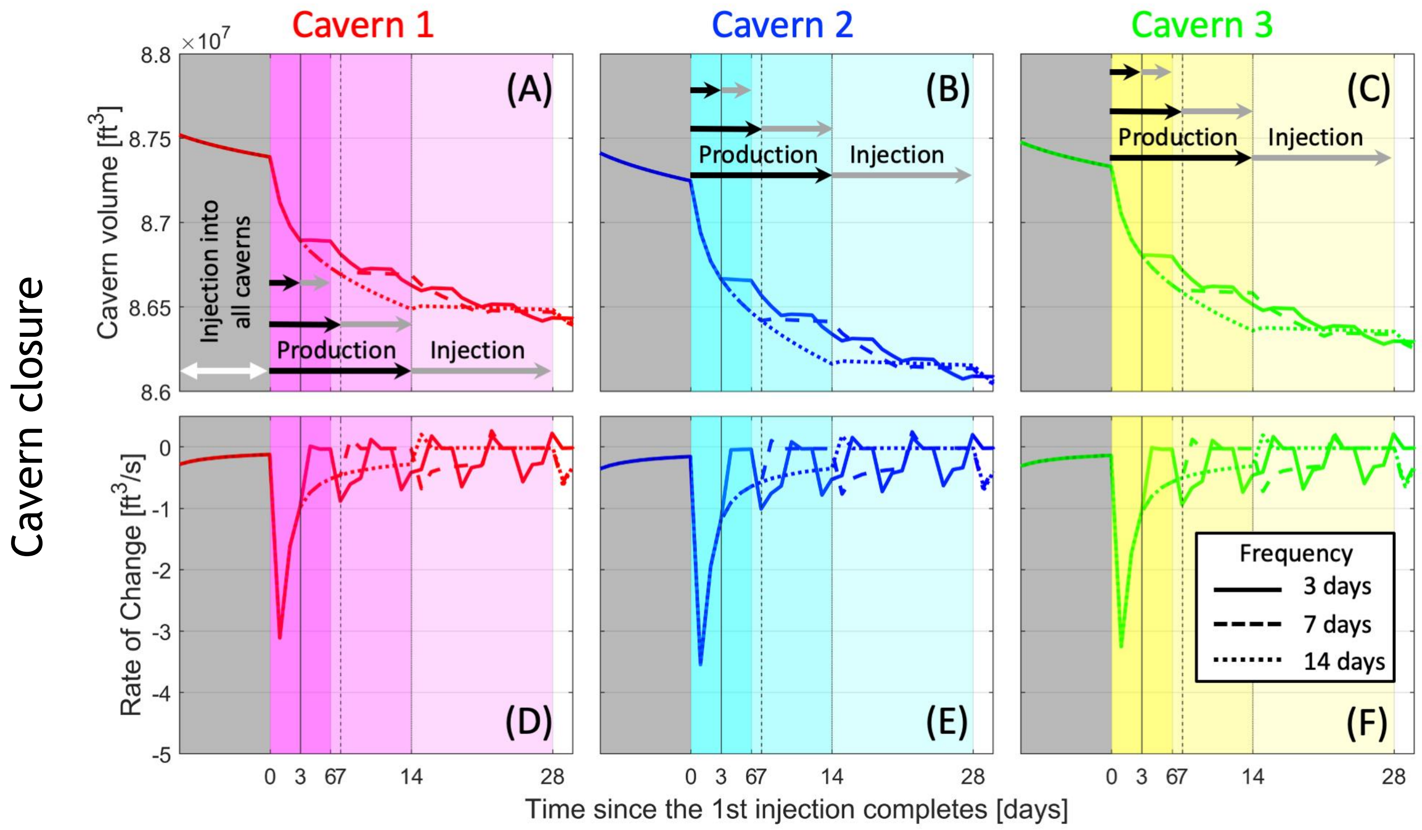


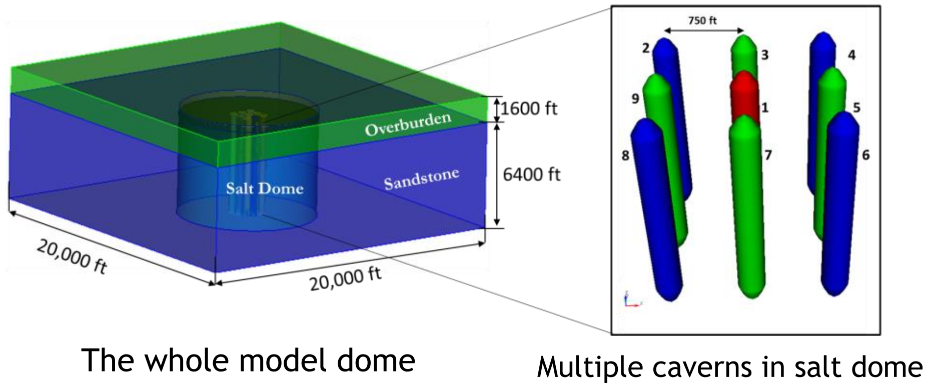
The whole model dome

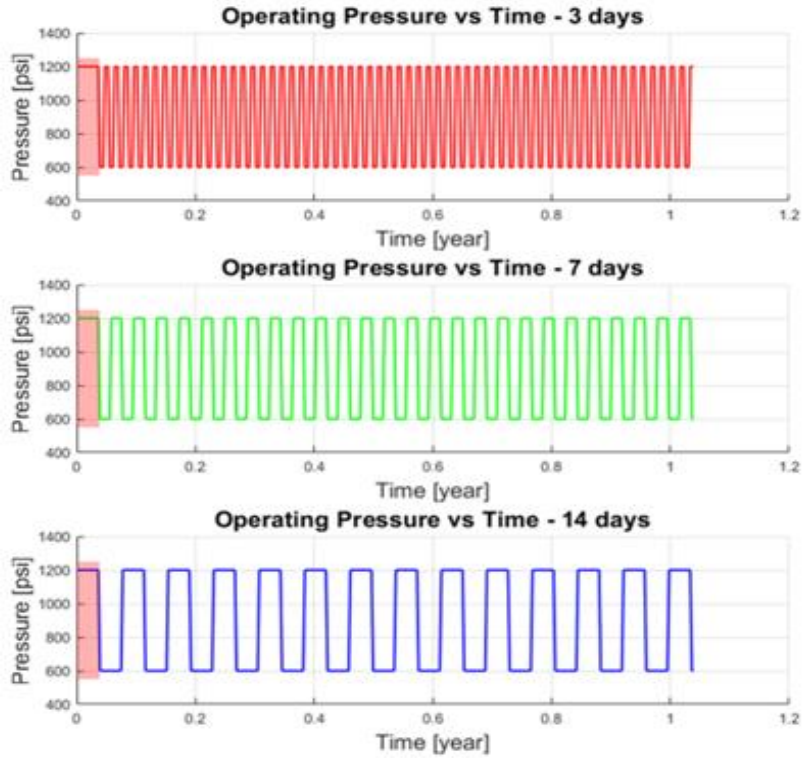
Multiple caverns in salt dome

- 7 days of cyclic operation
- 600 psi (≈ 4 MPa) of pressure difference b/w injection and production
- **Initial production** has the most significant impact.
- **Center** cavern has the **least cavern closure** due to impact of surrounding caverns

Result: CASE 2 – Frequency of Operation

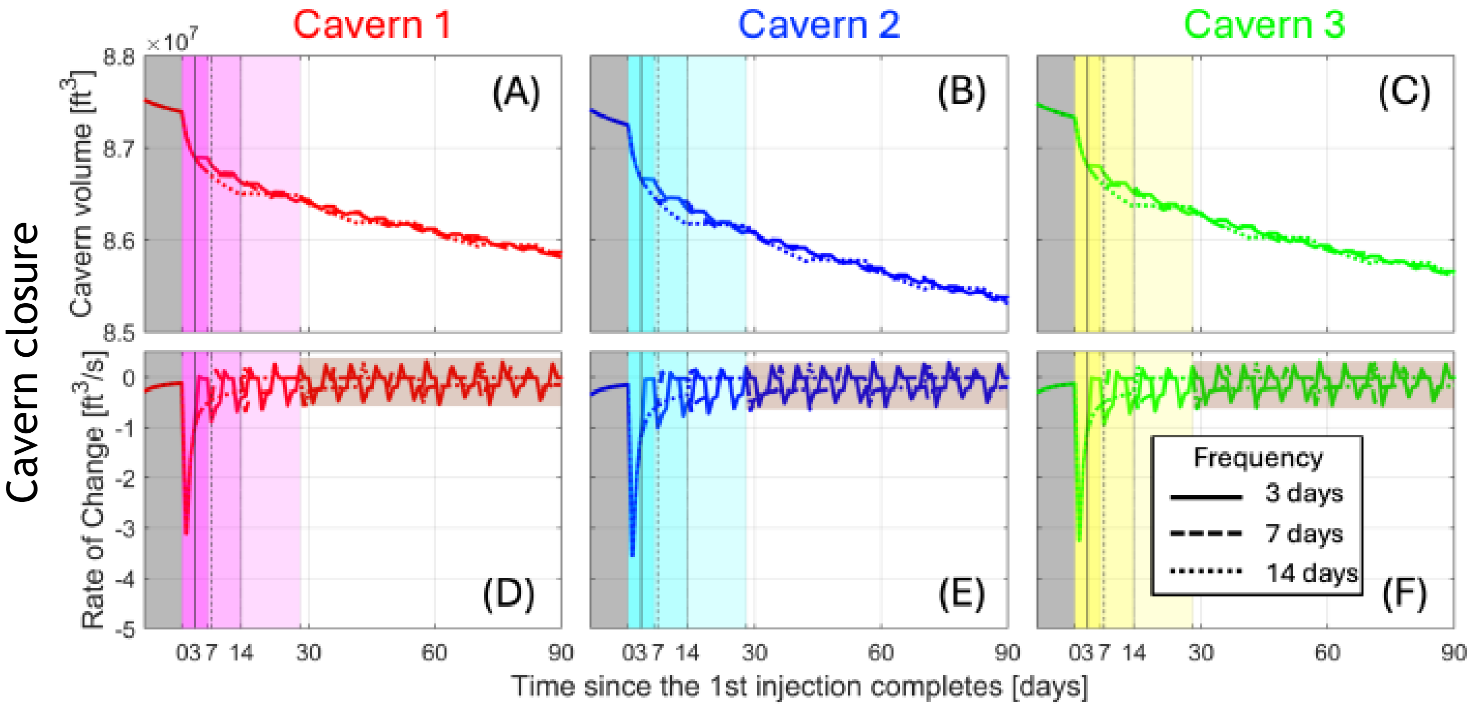


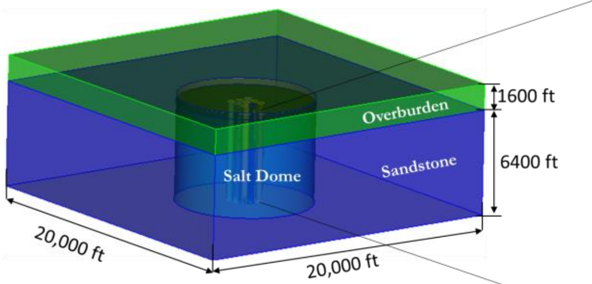




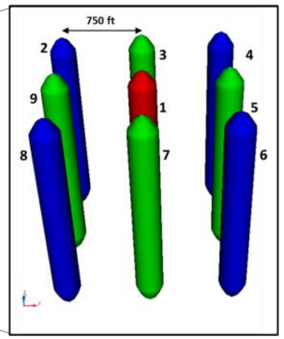
- 3, 7, and 14 days of cyclic operations
- Pressure difference of 600 psi

Result: CASE 2 – Frequency of Operation

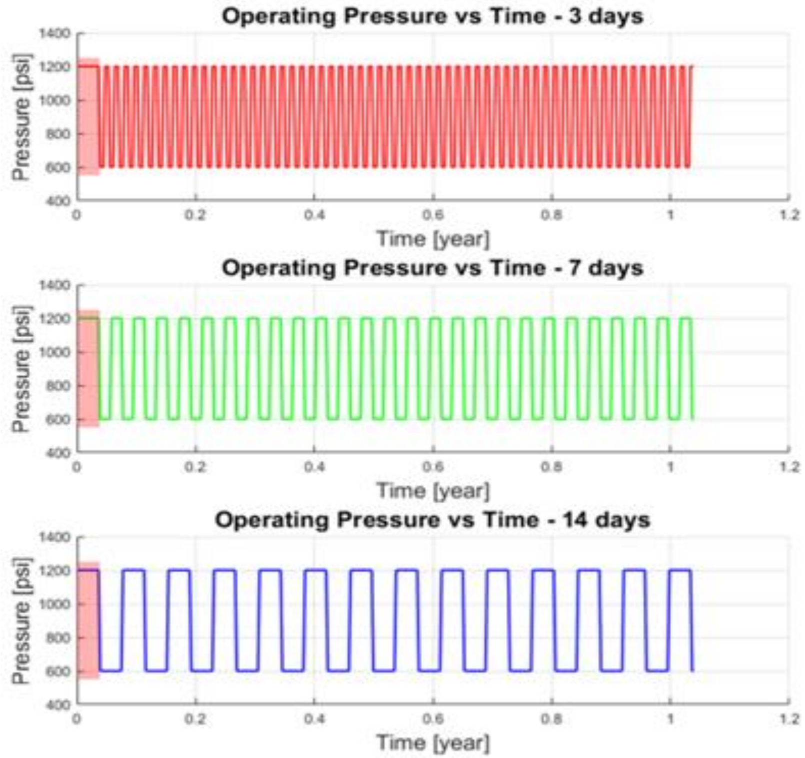




The whole model dome

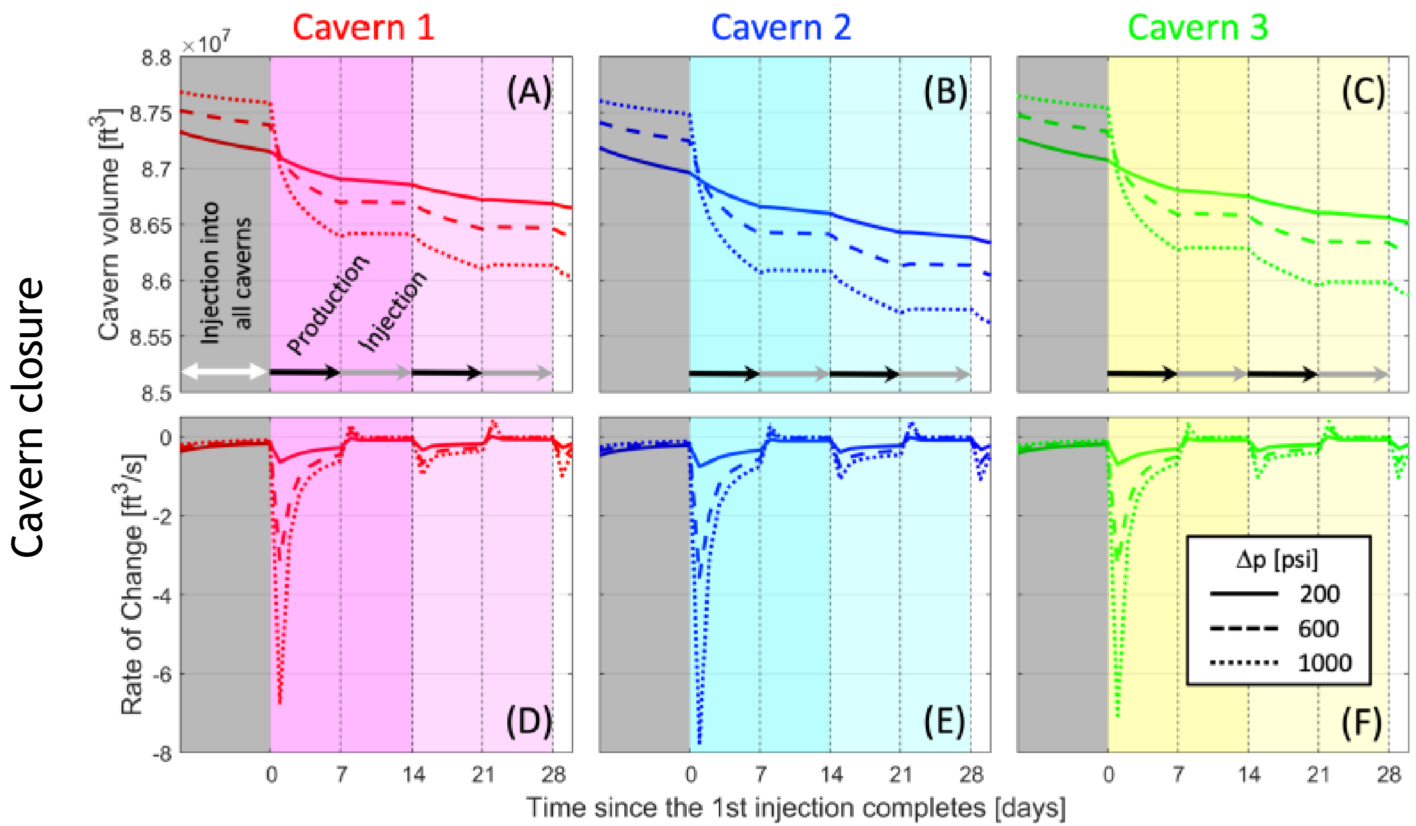


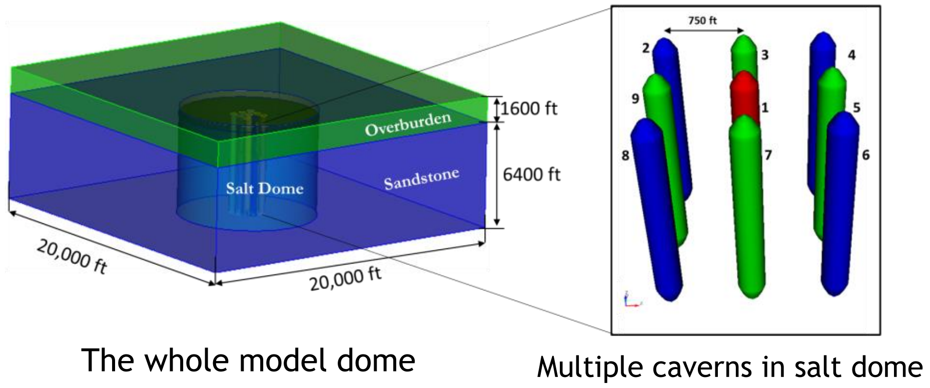
Multiple caverns in salt dome

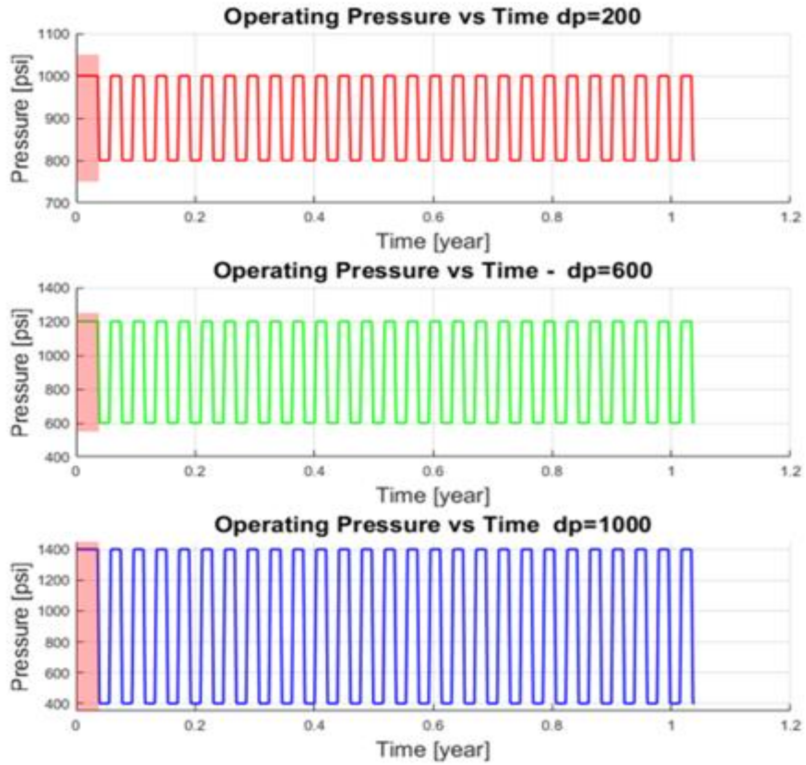


- 3, 7, and 14 days of cyclic operations
- Pressure difference of 600 psi
- After 30 days, the effect of cycle frequency on cavern volume stabilizes within a certain range for all caverns, indicating a **consistent rate of creep closure**.

Result: CASE 3 – Magnitude of Cavern Pressure

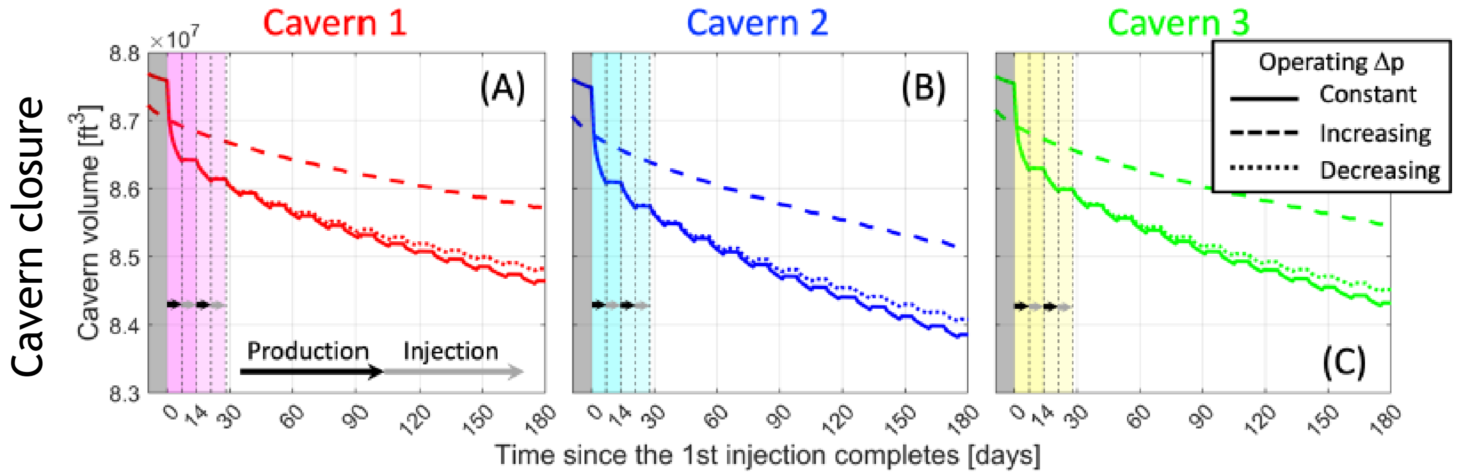


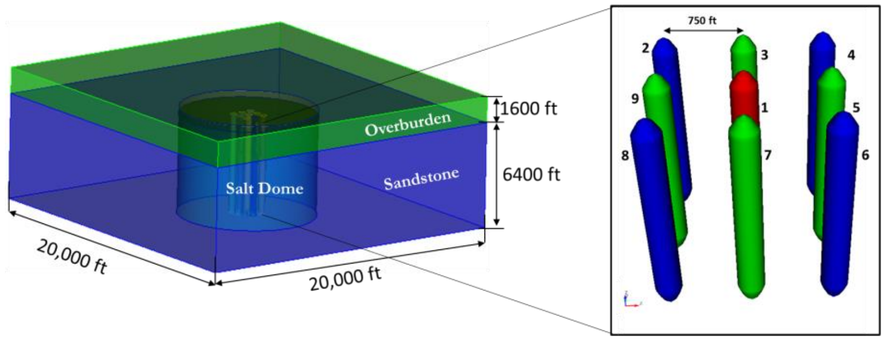




- 7 days of cyclic operation
- Differential pressure (Δp) of 200, 600, and 1000 psi
- **Higher differential pressure (Δp)** leads to increase and **accelerate** cavern creep closure

Result: CASE 3 – Magnitude of Cavern Pressure

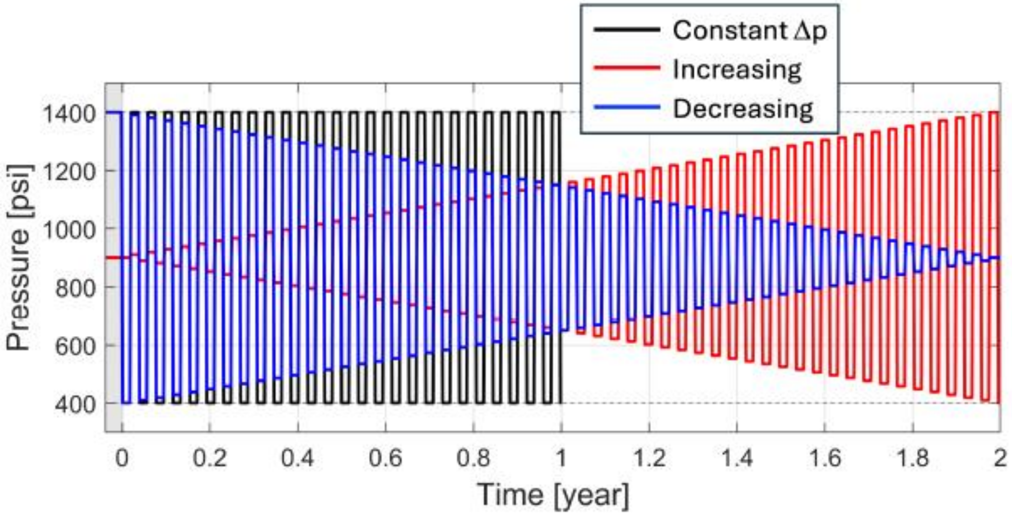




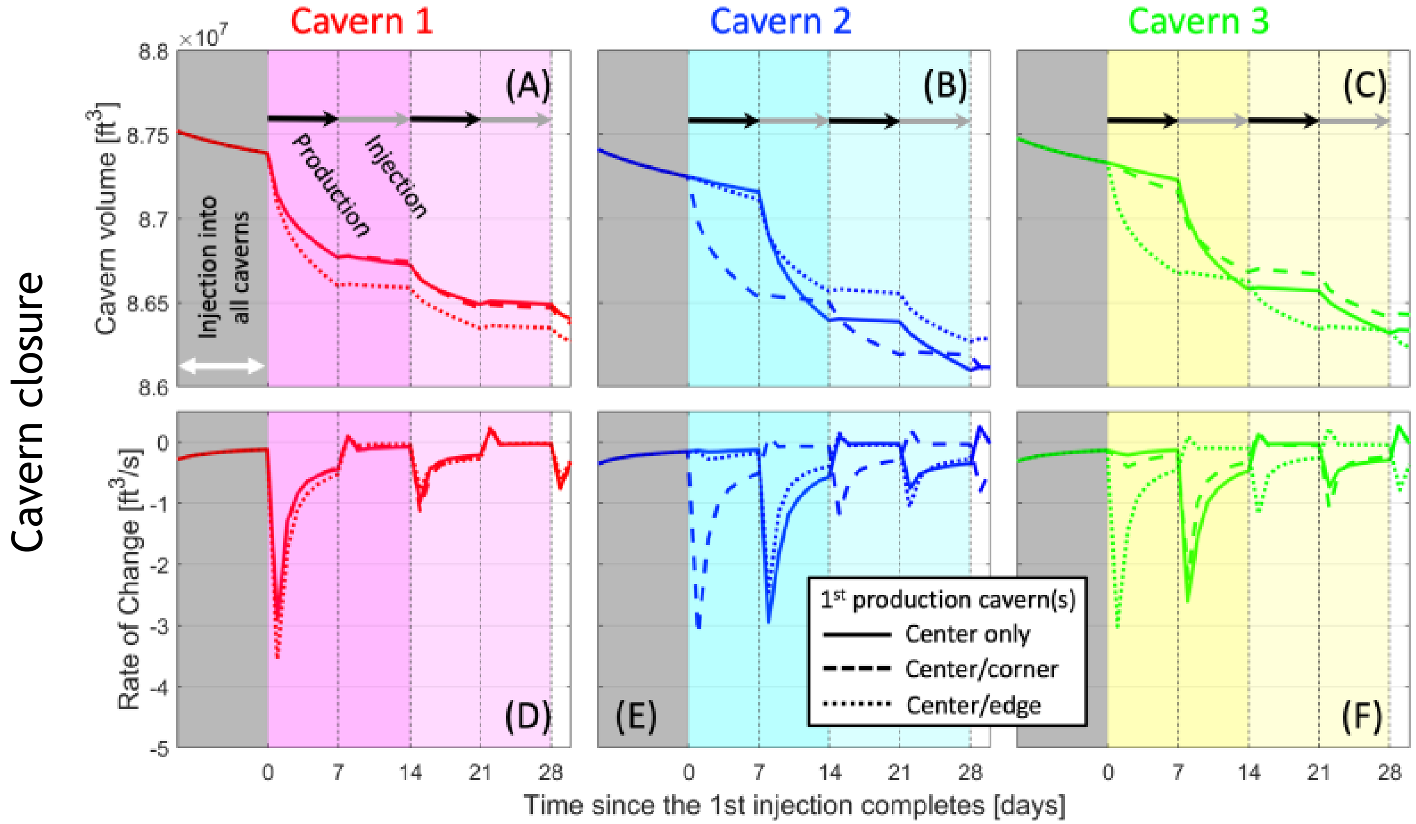
The whole model dome

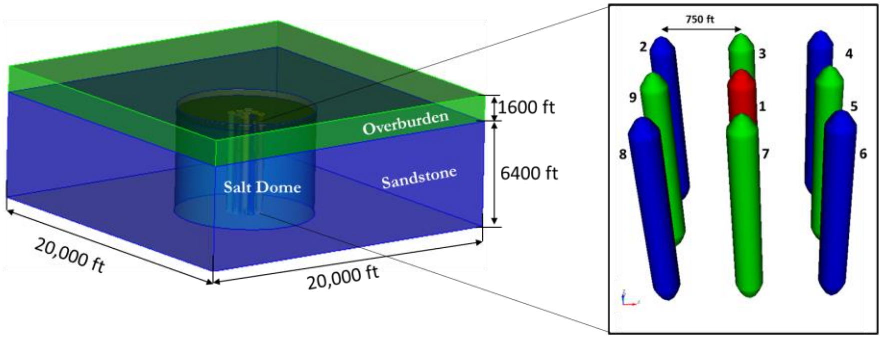
Multiple caverns in salt dome

- Gradually **increasing Δp** during operation significantly **reduces** initial and subsequent **cavern closure**, suggesting that starting with a **lower Δp** can mitigate the **geomechanical effects of cyclic operations** on salt creep and deformation.



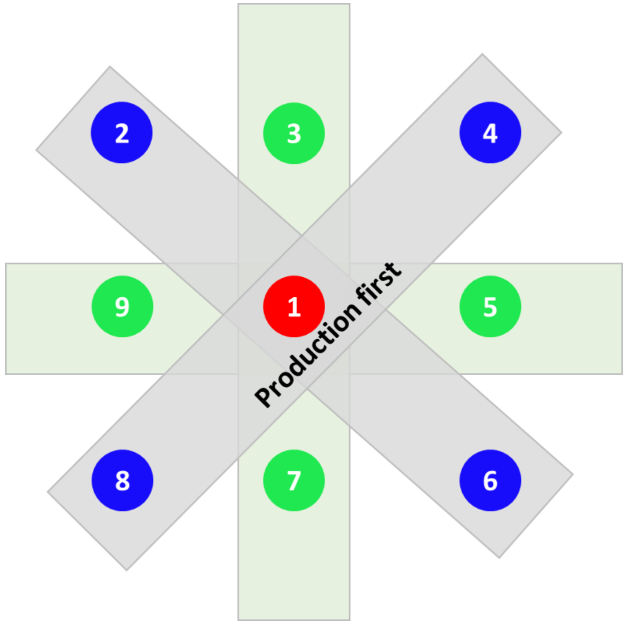
Result: CASE 4 – Sequential Order of Operating Cavern





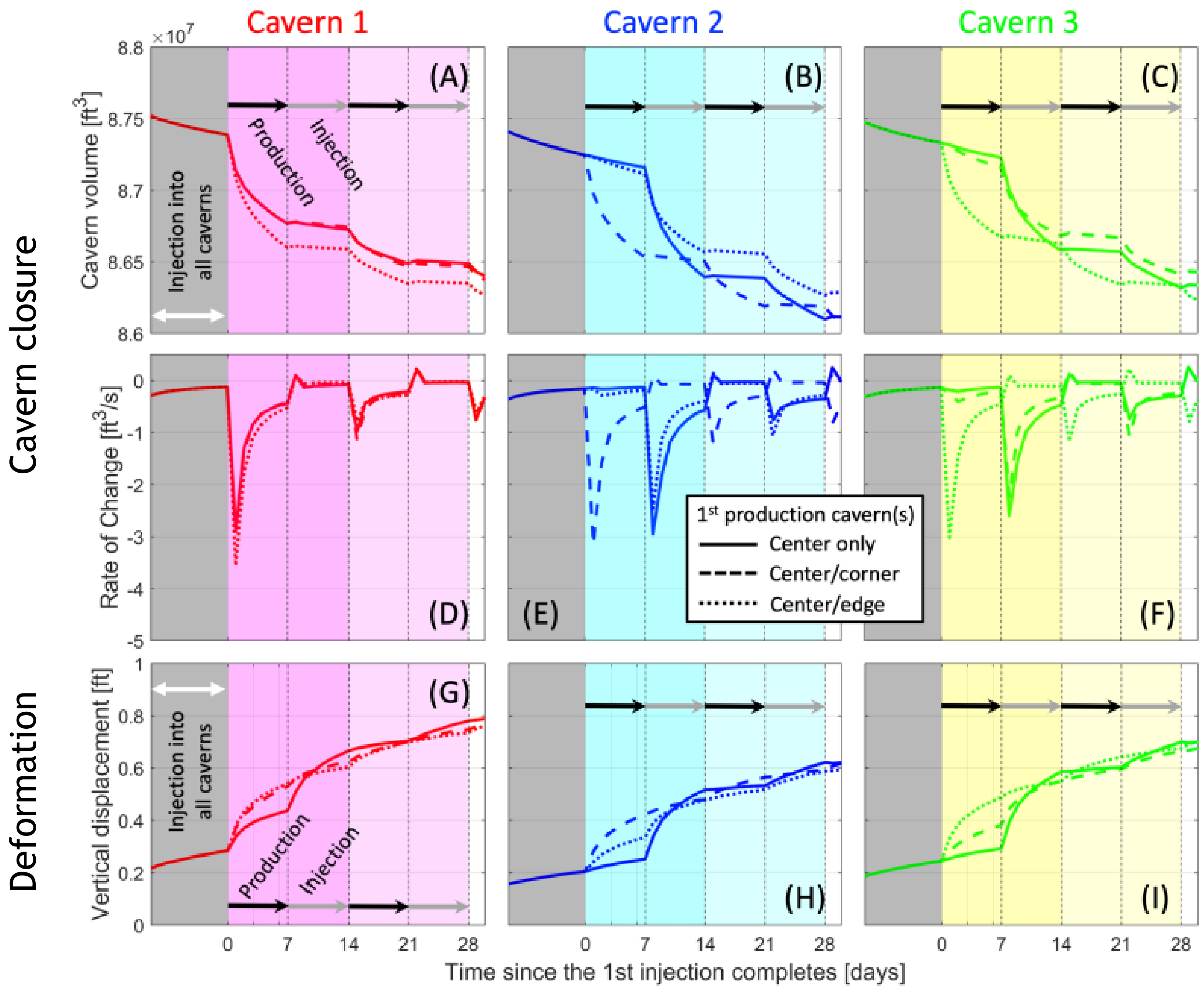
The whole model dome

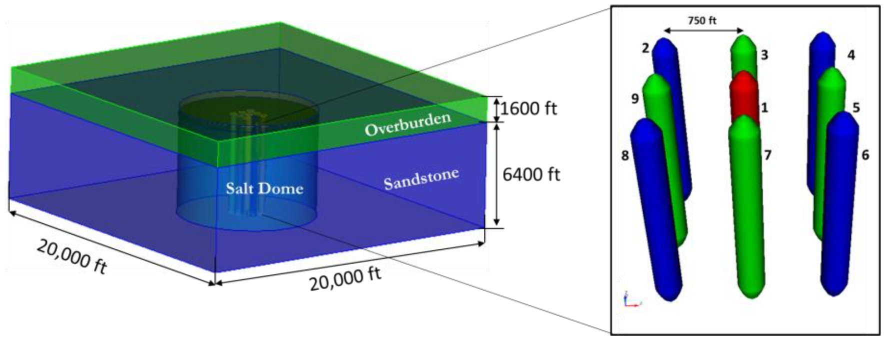
Multiple caverns in salt dome



- 7 days of cyclic operation
- Pressure difference of 600 psi
- Operating **closer** caverns can **accelerate creep closure** due to stronger lateral creep (Figure A; case of production first from center and edge (green) caverns)

Result: CASE 4 – Sequential Order of Operating Cavern





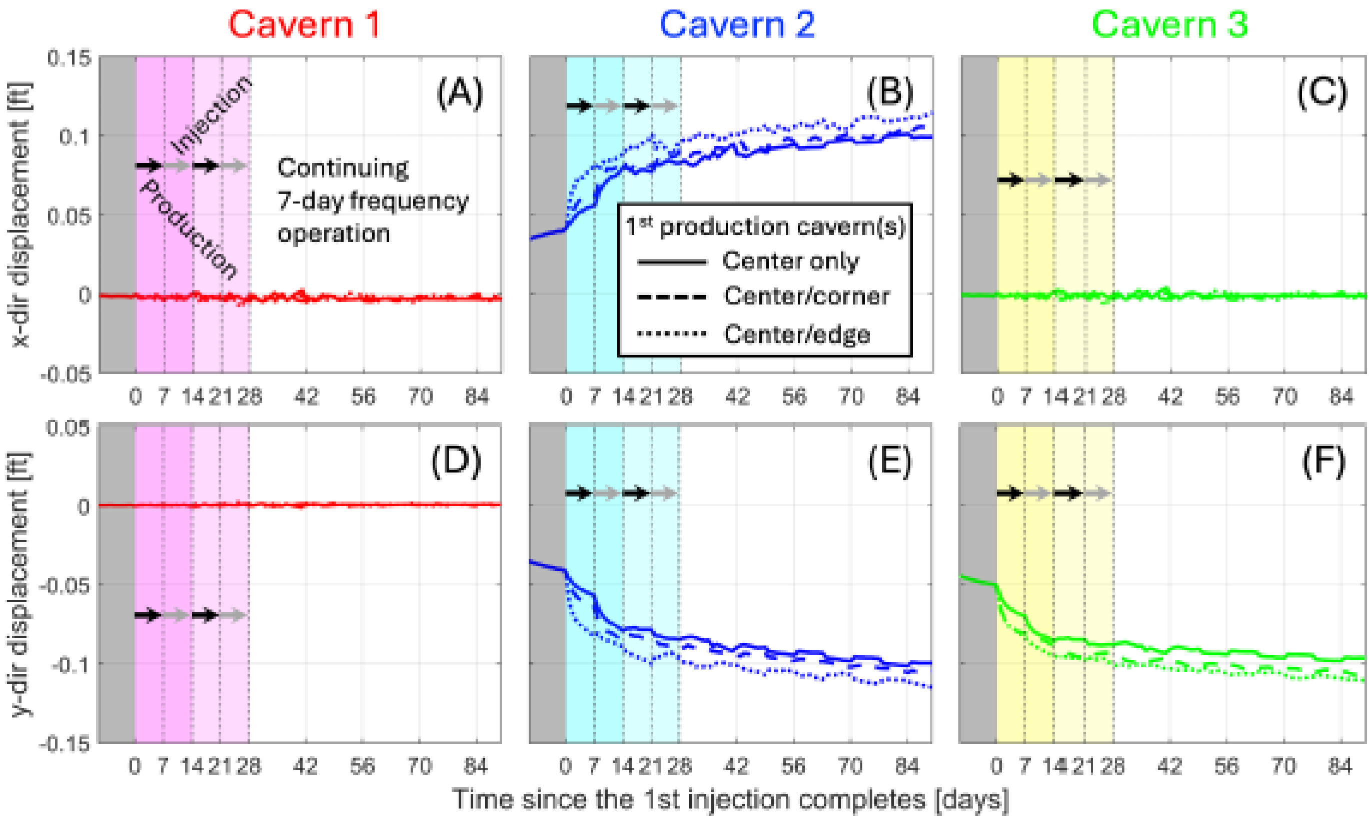
The whole model dome

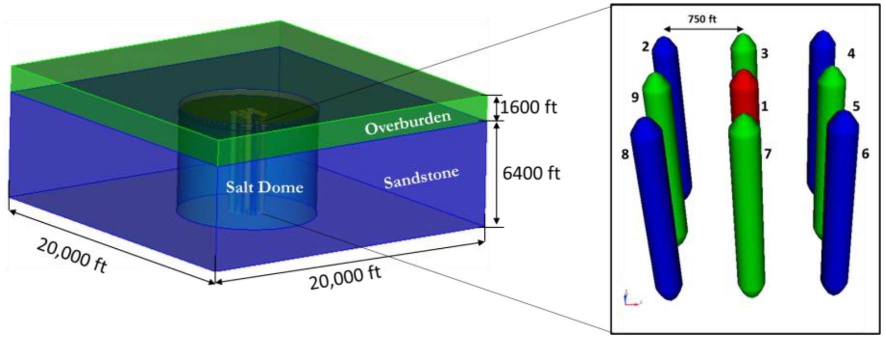
Multiple caverns in salt dome

- The center cavern experiences the **largest vertical displacement** when production starts at the center and edge caverns (Figure G), indicating that principal stresses normal to cavern walls are crucial in governing geomechanical interactions.

Result: CASE 4 – Sequential Order of Operating Cavern

Deformation





The whole model dome

Multiple caverns in salt dome

- **Cavern Interactions:** The center cavern (Cavern 1) shows minimal lateral deformation due to surrounding caverns, while the corner cavern (Cavern 2) deforms significantly in the direction free of neighbors.
- **Deformation:** Initial production leads to rapid displacements, with edge caverns (Cavern 3) constrained in the x-direction but deforming in the y-direction, indicating that principal stresses are key to cavern interactions.

Conclusion and Future Work

- ✓ **Impact of Cyclic Loading:** Our 3D simulation results highlight the effects of cyclic loading-unloading on multiple storage caverns, revealing significant insights into salt creep behavior and geomechanical deformation.
- ✓ **Cavern Volume Loss Dynamics:** The most substantial volume loss occurs during the initial production stage, but continuous cyclic operation stabilizes the rate of cavern volume change.
- ✓ **Creep Closure Rate Convergence:** Under consistent operational pressure, the creep closure rate stabilizes across varying cycle frequencies, while larger pressure differentials accelerate cavern volume closure and deformation.
- ✓ **Sequential Cavern Behavior:** The order of cavern operation influences the initial step-wise volume decrease and subsidence, indicating that cavern arrangement is crucial for performance.
- ✓ **Lateral Interactions:** The interaction between adjacent caverns can alter stress states, affecting cavern performance and wellbore integrity, emphasizing the importance of cavern arrangement.

<u>Need for Improved Models</u>

- ➢ Current salt constitutive models overlook critical factors like transient reverse creep and damage-healing mechanisms, potentially driven by cyclic operations.
- ➢ Future work will focus on developing a physics-based salt material model informed by geomechanical tests under cyclic loadings, enhancing guidance for underground energy storage in salt formations.

Questions?

Approach

This project aims to **develop a new salt constitutive model** considering

1. **Frequent cycles of operation**
2. **Gaseous H_2**
3. **Domal salt**

based on

1. geomechanical **core-testing results** and pore-scale analysis with variation in loading-unloading conditions,
2. which will be **integrated into Sandia's finite-element simulation code** (Sierra/SolidMechanics) for
3. the **field-scale assessment** of underground H_2 storage.

Workflow of Geomechanical Analysis

Material constitutive model
Viscoplastic behavior of salt

Geomechanical lab test
Parameters for constitutive model

Geometric information
Cavern (sonar data)
Dome (seismic/borehole data)

Operation state
Well head pressure
Fluid interface depth, if needed

Workflow of Geomechanical Analysis

Material constitutive model
Viscoplastic behavior of salt

Geomechanical lab test
Parameters for constitutive model

Geometric information
Cavern (sonar data)
Dome (seismic/borehole data)

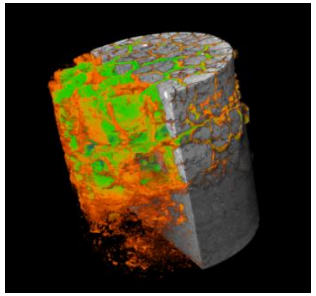
Operation state
Well head pressure
Fluid interface depth, if needed

Cavern volume calculation ⇒

Subsidence survey
InSAR/GPS ⇒

Model calibration
Setup of subroutine for Sierra/SM
Operating pressure within caverns

Workflow of Geomechanical Analysis



Material constitutive model
Viscoplastic behavior of salt

Geomechanical lab test
Parameters for constitutive model

Geometric information
Cavern (sonar data)
Dome (seismic/borehole data)

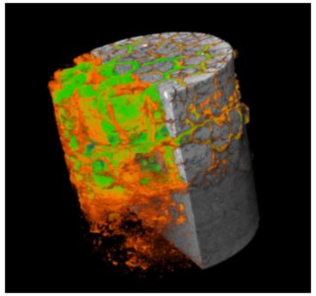
Operation state
Well head pressure
Fluid interface depth, if needed

Cavern volume calculation ⇨

Subsidence survey
InSAR/GPS ⇨

Model calibration
Setup of subroutine for Sierra/SM
Operating pressure within caverns

Workflow of Geomechanical Analysis



Material constitutive model
Viscoplastic behavior of salt

Geomechanical lab test
Parameters for constitutive model

Geometric information
Cavern (sonar data)
Dome (seismic/borehole data)

Operation state
Well head pressure
Fluid interface depth, if needed

Cavern volume calculation

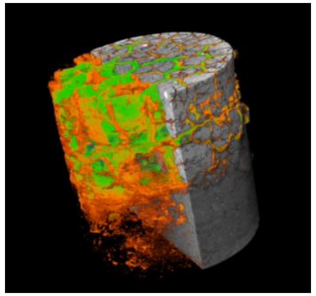
Subsidence survey
InSAR/GPS

→ **Geomechanical simulation**
Sierra/SolidMechanics runs in SNL's High-Performance Computing platform

Model calibration
Setup of subroutine for Sierra/SM
Operating pressure within caverns

↑ (Model calibration → Geomechanical simulation)

Workflow of Geomechanical Analysis



Material constitutive model
Viscoplastic behavior of salt

Geomechanical lab test
Parameters for constitutive model

Geometric information
Cavern (sonar data)
Dome (seismic/borehole data)

Operation state
Well head pressure
Fluid interface depth, if needed

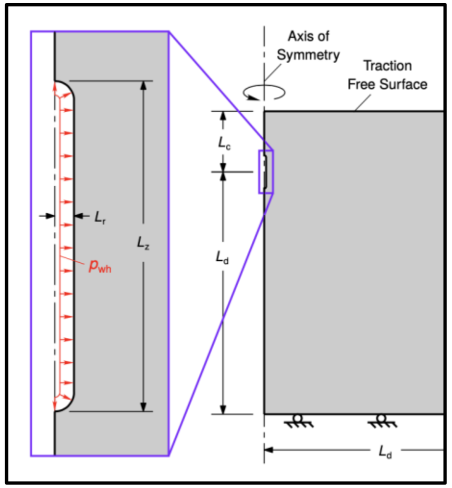
Cavern volume calculation

Subsidence survey
InSAR/GPS

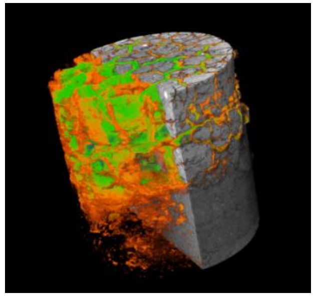
Geomechanical simulation
Sierra/SolidMechanics runs in SNL's High-Performance Computing platform

Model calibration
Setup of subroutine for Sierra/SM
Operating pressure within caverns

Simple model validation



Workflow of Geomechanical Analysis



Material constitutive model
Viscoplastic behavior of salt

Geomechanical lab test
Parameters for constitutive model

Geometric information
Cavern (sonar data)
Dome (seismic/borehole data)

Operation state
Well head pressure
Fluid interface depth, if needed

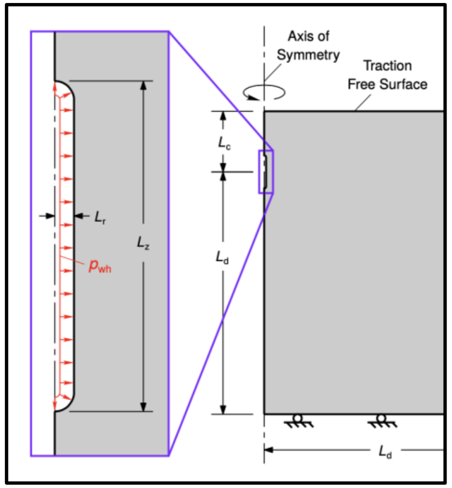
Cavern volume calculation

Subsidence survey
InSAR/GPS

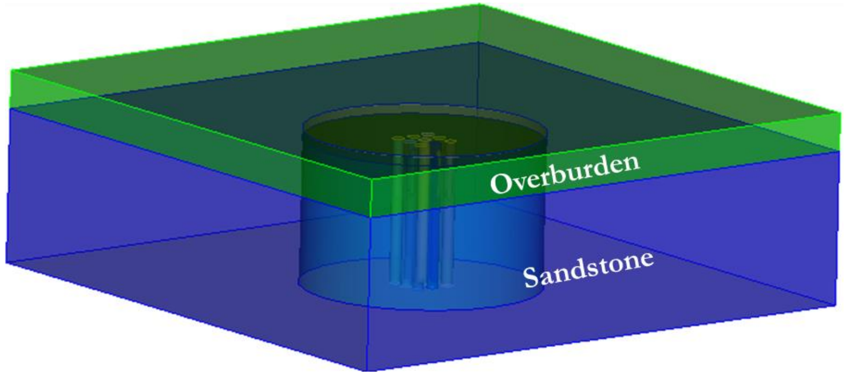
Geomechanical simulation
Sierra/SolidMechanics runs in SNL's High-Performance Computing platform

Model calibration
Setup of subroutine for Sierra/SM
Operating pressure within caverns

Simple model validation



Generic multi-cavern model



M-D Creep Constitutive Equations (Steady State)

- Modeling utilizes M-D Creep and M-D Viscoplastic equations to model the behavior of salt.

  - Steady state creep rate: $\dot{\varepsilon}_s = \sum_{i=1}^{3} \dot{\varepsilon}_{s_i}$

    1. Dislocation climb controlled creep mechanism at high temperatures and low stresses:

$$\dot{\varepsilon}_{s_1} = A_1 e^{-\frac{Q_1}{RT}} \left[\frac{\sigma}{\mu(1-\omega)}\right]^{n_1}$$

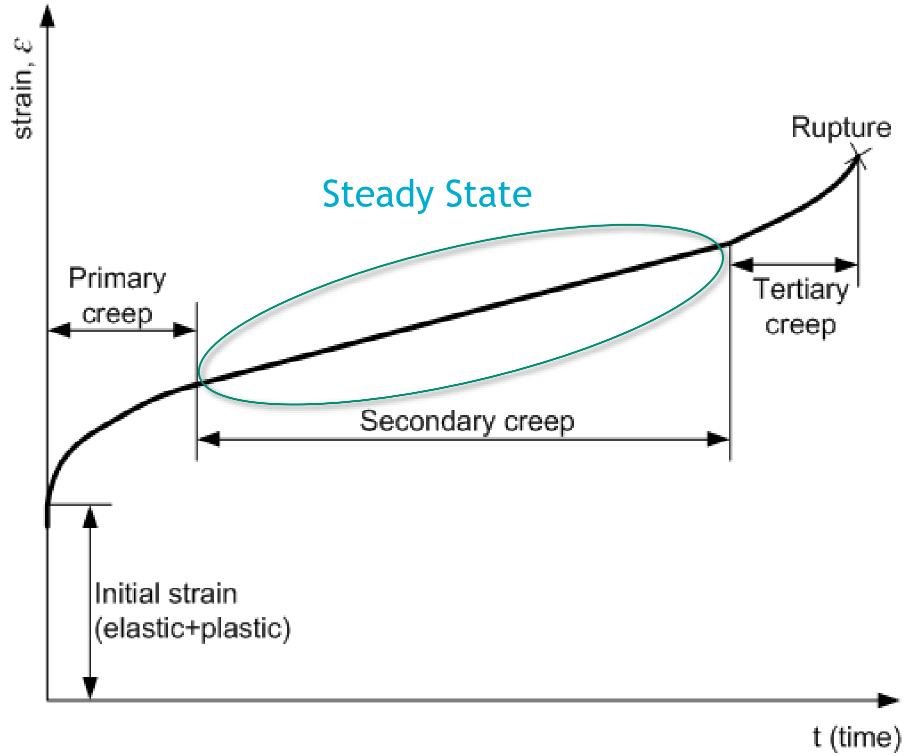
2. Empirically specified but undefined mechanism at **low temperatures and medium stresses (10 MPa – 25 MPa)**:

$$\dot{\varepsilon}_{s_2} = A_2 e^{-\frac{Q_2}{RT}} \left[\frac{\sigma}{\mu(1-\omega)}\right]^{n_2}$$

3. Dislocation slip controlled mechanism at high stresses:

$$\dot{\varepsilon}_{s_3} = |H(\sigma-\sigma_0)| \left(B_1 e^{-\frac{Q_1}{RT}} + B_2 e^{-\frac{Q_2}{RT}}\right) \sinh\left[\frac{q\left(\frac{\sigma}{1-\omega}-\sigma_0\right)}{\mu}\right]$$

[Munson, et al., 1989].



Where:

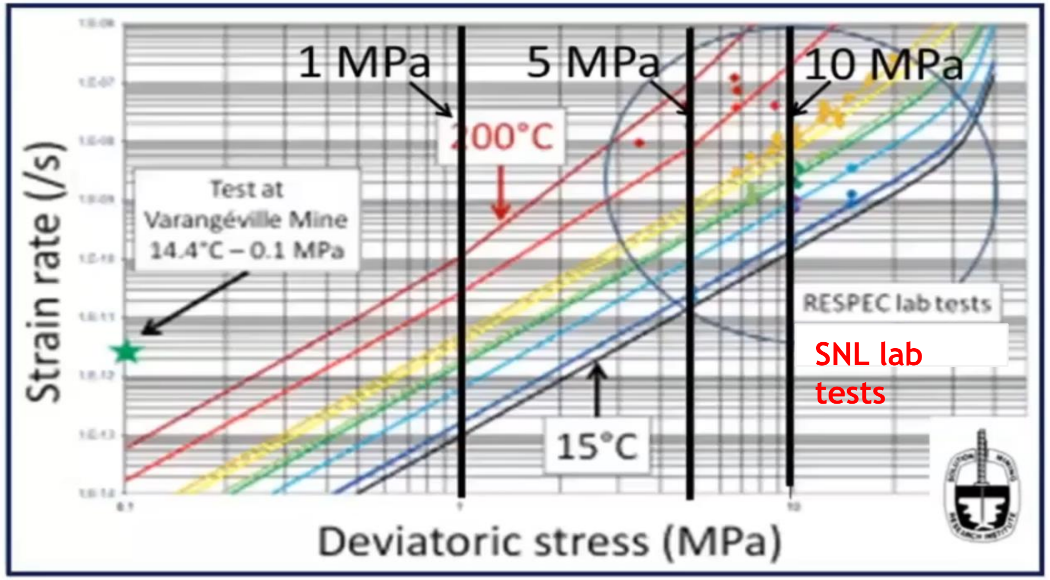
A's and *B*'s = structure factors,
Q's = activation energies,
R = universal gas constant
T = absolute temperature,
μ = shear modulus,
q = stress constant,
σ_0 = stress limit,
H = Heaviside step function with argument (σ-σ_0)

Munson-Dawson (M-D) Model with Loading-Unloading Condition

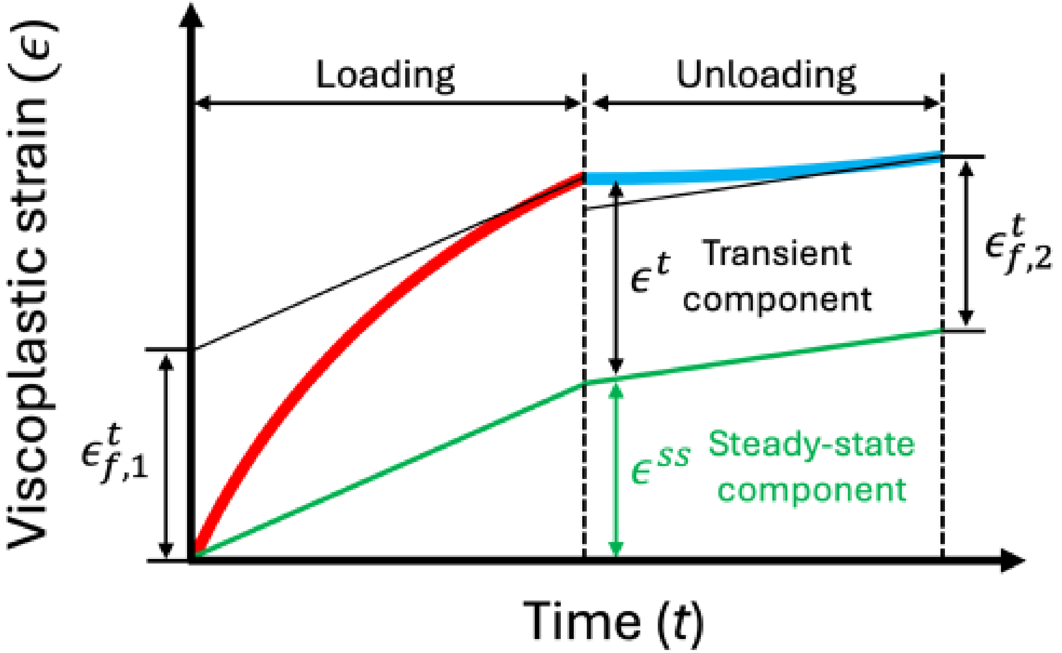
- **Transient Creep Behavior:** Transient creep initiates immediately upon loading, exhibiting a decrease in strain over time until a steady state is achieved, where the transient strain limit is established.

- **Response to Unloading:** Upon unloading, the total strain rate decreases initially; however, the salt creep gradually approaches a new steady state that corresponds to the adjusted stress level.

$$\varepsilon_t^* = K_0 e^{cT} \left(\frac{\sigma}{\mu(1-\omega)} \right)^m$$



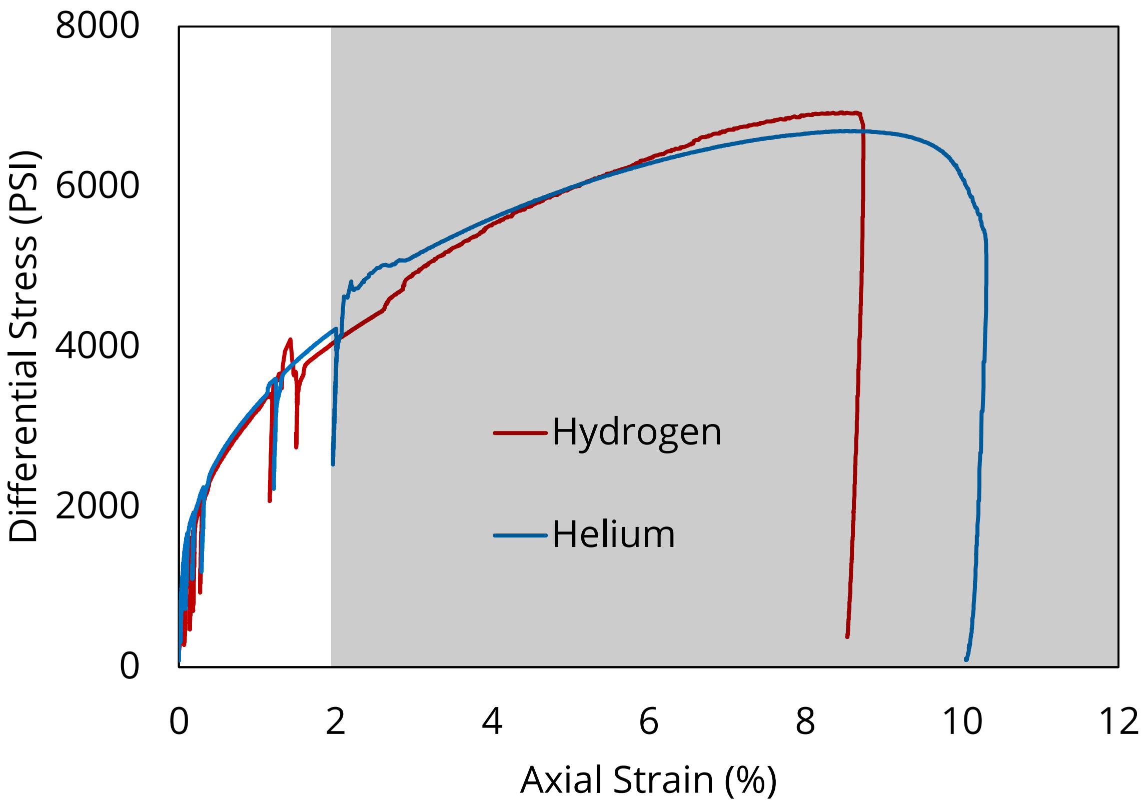
Berest et al., 2020



Transient strain ε_t^* dominates during large pressure change activities; Coefficient K_0 also determined from lab tests.

Technical Accomplishments – Task 1

- Validation test for Helium use (SNL)



- ➢ Core to 3.5” diameter sample jacketed with UV cure polyurethane
- ➢ Initially held at 2000 PSI confining pressure, 50°C to allow salt to heal
- ➢ Pore space evacuated, exposed to gas flow across sample length
- ➢ For axial deformation, pressure dropped and temperature reduced to ambient
  - ✓ as set to constant, static pressure
  - ✓ Effective pressure of 2 Mpa
- ➢ Investigating dilatant behavior, fracture driven deformation

- ➢ Tests ended after reaching limits of Schuler gages (only 1 Schuler gage functional)
- ➢ High strain reached
- ➢ Sample starts dilating after 2000 PSI differential stress; Heavily fractured samples
- ➢ Similar behavior up to 2% strain (similar unload-reload loops)
- ➢ Max stress attained within 5% for both samples

Mechanical behavior similar for salt saturated with hydrogen, helium

Generic Multi-Cavern Model Setup

- **Munson-Dawson creep model** with (1) 3 steady-state (SS) creep mechanisms and (2) transient mechanism
  - ✓ SS mechanism 2 dominates at low temperatures and medium equivalent stresses, is dominant mechanism measured in laboratory creep tests of SPR and Waste Isolation Pilot Plant (WIPP) salts [Munson, 1998].

$$\dot{\varepsilon}^{ss} = \sum_{i=0}^{3} \dot{\varepsilon}_i^{ss}$$

$$\dot{\varepsilon}_i^{ss} = A_i \exp\left(-\frac{Q_i}{RT}\right)\left(\frac{\sigma_{eq}}{\mu}\right)^{n_i} \quad \text{for } i = 1, \text{and } 2$$

  - ✓ Transient strain ε_t^* dominates during large pressure change activities; Coefficient K_0 also determined from lab tests.

$$\varepsilon_t^* = K_0 e^{cT}\left(\frac{\sigma}{\mu(1-\omega)}\right)^m$$

- **Elastic behavior in all layers** except salt
- Simulation timeline – 1003 years + 14 days
  - ✓ Equilibration phase – 1001 year
  - ✓ Leaching phase – 1 year
  - ✓ Injection to fill all caverns – 14 days
  - ✓ Operation phase – 1 year for cyclic injection and production

Table 2: Parameters of the M-D creep model for salt rock

Parameter	Value
Density [lb/ft^3]	143.58 (2300 kg/m^3)
Elastic modulus [lb/ft^2]	6.48×10^8 (31.0 GPa)
Shear modulus (G) [lb/ft^2]	2.59×10^8 (12.4 GPa)
Poisson's ratio (ν) [–]	0.25
Steady-state mechanism 1	
Primary creep constant (A_1) [1/sec]	9.81×10^{22}
$n_1^\dagger$	5.5
$Q_1^\dagger$ [cal/mol]	25
Steady-state mechanism 2	
Secondary creep constant (A_2)* [1/sec]	11.32×10^{12}
n_2^*	5.0
$Q_2^\dagger$ [cal/mol]	10
Steady-state mechanism 3	
B_1 [1/sec]	7.12×10^6
B_2 [1/sec]	3.55×10^{-2}
σ_0 [lb/ft^2]	4.29×10^3 (20.57 MPa)
q	5.335×10^3
Transient mechanism	
$m^\dagger$	3.0
K_0	6.275×10^5
c	0.00511
α	-17.37
β	-7.738
δ	0.58
ω	0

Generic Multi-Cavern Model Setup

- **Munson-Dawson creep model** with (1) 3 steady-state (SS) creep mechanisms and (2) transient mechanism
  - ✓ SS mechanism 2 dominates at low temperatures and medium equivalent stresses, is dominant mechanism measured in laboratory creep tests of SPR and Waste Isolation Pilot Plant (WIPP) salts [Munson, 1998].

$$\dot{\varepsilon}^{ss} = \sum_{i=0}^{3} \dot{\varepsilon}_i^{ss}$$

$$\dot{\varepsilon}_i^{ss} = A_i \exp\left(-\frac{Q_i}{RT}\right)\left(\frac{\sigma_{eq}}{\mu}\right)^{n_i} \quad \text{for } i = 1, \text{and } 2$$

  - ✓ Transient strain ε_t^* dominates during large pressure change activities; Coefficient K_0 also determined from lab tests.

$$\varepsilon_t^* = K_0 e^{cT}\left(\frac{\sigma}{\mu(1-\omega)}\right)^m$$

- **Elastic behavior in all layers** except salt
- Simulation timeline – 1003 years + 14 days
  - ✓ Equilibration phase – 1001 year
  - ✓ Leaching phase – 1 year
  - ✓ Injection to fill all caverns – 14 days
  - ✓ Operation phase – 1 year for cyclic injection and production

Sensitivity test	
CASE 1	• 600 psi operating pressure difference (Δp) • 7-day cycle (7 days of injection followed by 7days of production, totaling 14 days per cycle).
CASE 2	• 3, 7, and 14 days to assess the impact of high-frequency operations (weekly to monthly)
CASE 3	• Δp at 200, 600, and 1000 psi (max pressures of 1000, 1200, and 1400 psi) over one year • Gradual changes from 0 to 1000 psi over two years (400 to 1400 psi)
CASE 4	Sequentially operates multiple caverns with 3 scenarios: 1) center cavern only (Cavern 1) 2) Center/corner caverns (Caverns 1/2,4,6,8) 3) Center/edge caverns (Caverns 1/3,5,7,9).

Future Work

1. Geomechanical salt-core tests
   a. Validation of helium use (SNL)
   b. Viscoplastic/Healing-damage behaviors with cyclic loading-unloading (TAMU)

2. Development of a new salt constitutive model for Sierra/SolidMechanics code with material property calibration based on experimental outputs (SNL+TAMU)

3. Field-scale simulation with multiple cavern system and variation in operation scenarios (SNL)