

STRESS ANALYSIS OF A PRODUCTION CASING FOR A CAVERN DEVELOPED BENEATH AN EXISTING CAVERN FIELD



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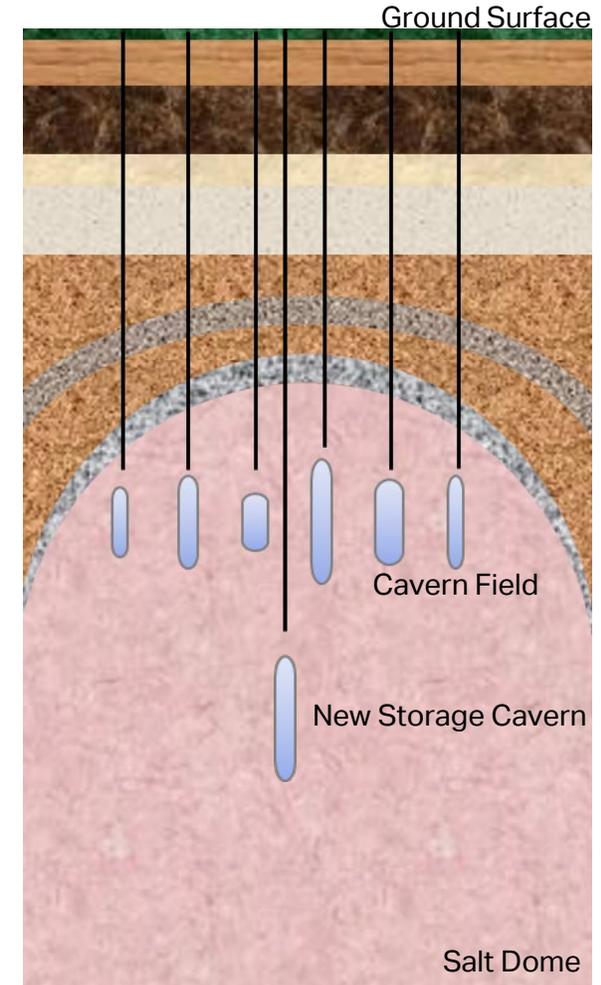
RAPID CITY, SD, USA

SMRI SPRING 2021 VIRTUAL TECHNICAL CONFERENCE

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INTRODUCTION

- › As storage cavern development continues within salt domes and older caverns reach the end of their service life, available space for new caverns is diminishing
- › Developing new caverns beneath an existing cavern field may be an option for certain facilities

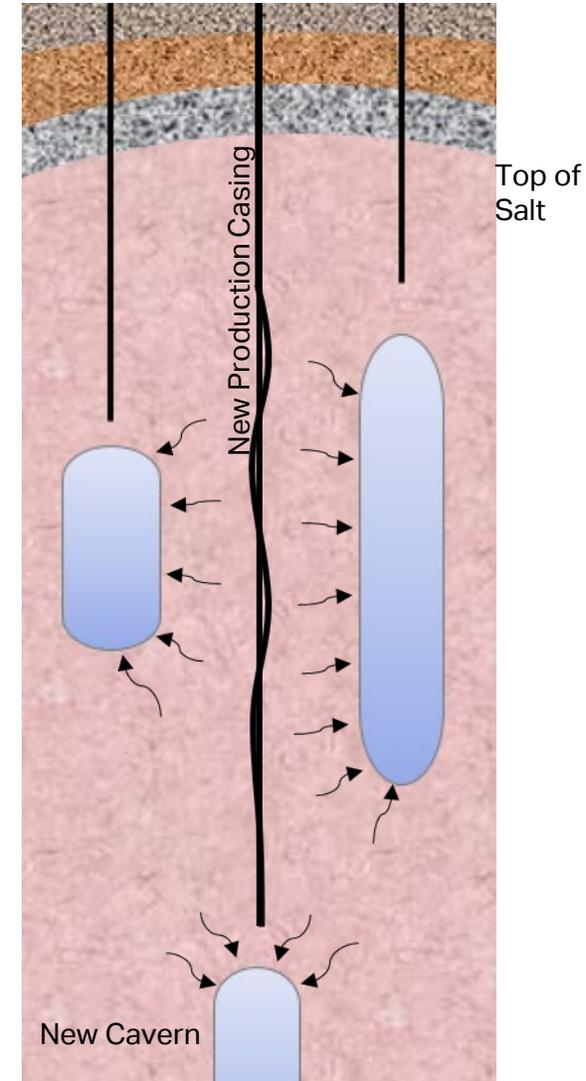


PROBLEM



RESPEC

- › Siting deeper caverns may require placing the new wells within close-proximity to one or more existing caverns
- › Creep closure of the nearby caverns will deform the well casing and potentially cause damage
- › Raises concerns for well integrity and operational service life



STUDY OBJECTIVES

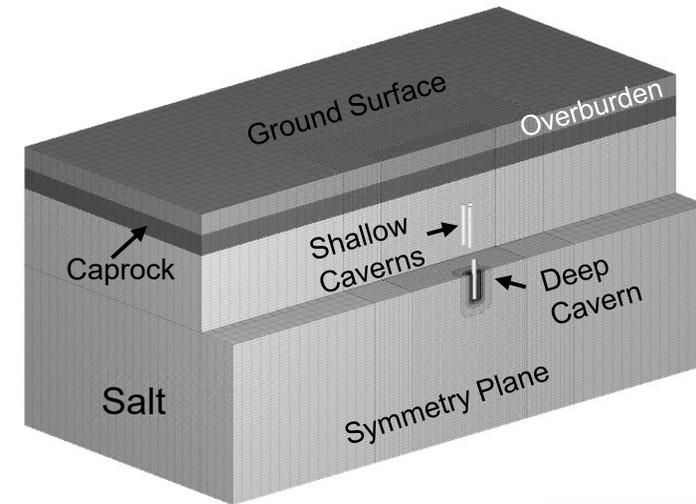
- › Evaluate a hypothetical liquid storage cavern development scenario and assess the future risk of damage to the well casing from creep closure of nearby caverns
- › Predict creep-induced casing deformation and estimate the future stress state in the well casing
- › Consider the effect of salt creep rate and spacing distance of the well from nearby caverns

APPROACH

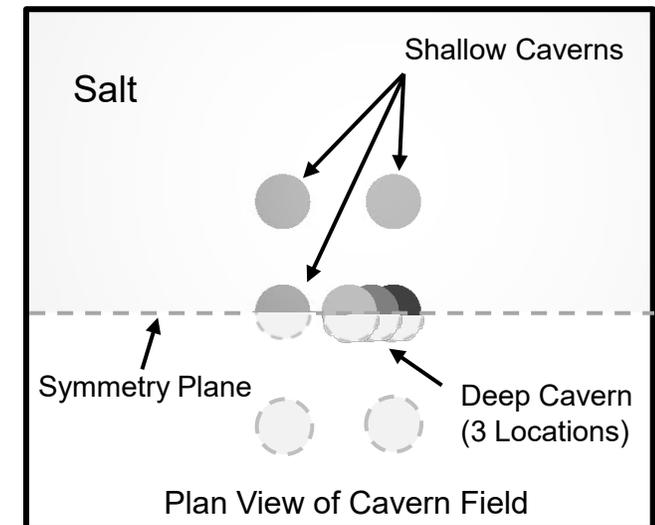
- › Three-dimensional (3D) numerical modeling to predict the future, creep-induced deformation of the well casing
- › Analytically estimate the future stress state in the well casing
- › Assess the risk of casing damage after 30 years of future operations and creep deformation

3D NUMERICAL MODEL

- › A 3D numerical model was developed to represent a subset of caverns within a hypothetical cavern field
 - / Assumed caverns are sufficiently distant from the dome flank to neglect edge-of-dome effects
 - / Five existing (shallow) caverns and a single future (deep) cavern
 - / Three of the shallow caverns were explicitly modeled, using symmetry to represent the cavern field
 - / Uniform thickness, horizontal stratigraphic units
 - » Overburden – 700 ft (213 m) thick
 - » Caprock – 700 ft (213 m) thick
 - » Domal Salt – 8,000 ft (2,438 m) thick



Isometric View with Cut-Away



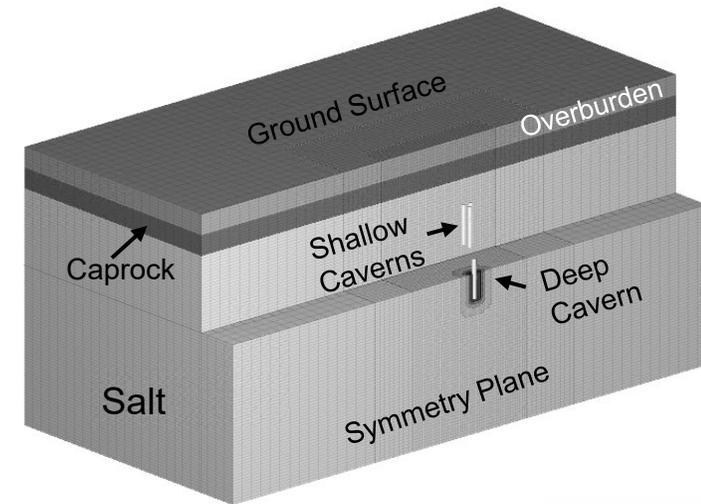
3D NUMERICAL MODEL - CAVERNS

› Simple, right-cylinder cavern geometry

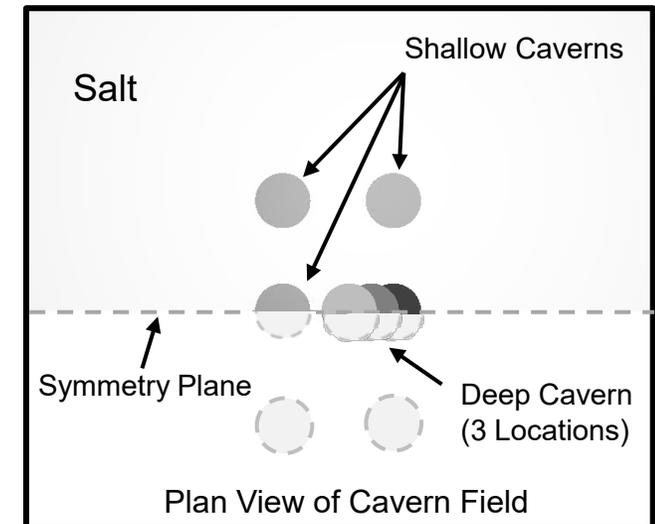
- / All caverns are the same size & shape
- / 150 ft (45.7 m) diameter
- / 1,350 ft (411.5 m) height
- / 4.25 MMbbls (0.675 MM m³)

› Shallow caverns

- / Roof depth, 1,700 ft (518 m)
- / Spacing, $P:D^1 = 1.0$
 - » Closely spaced caverns



Isometric View with Cut-Away

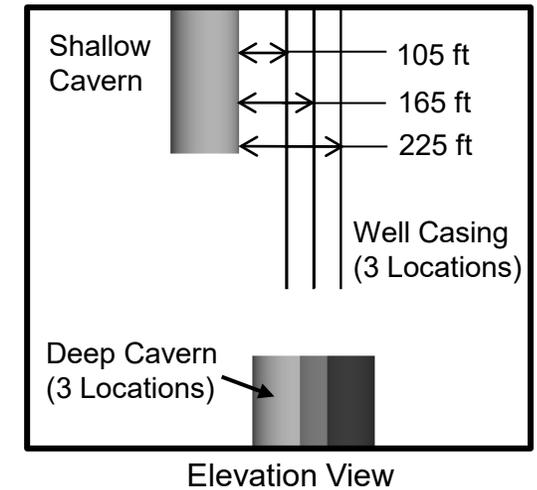


¹ P:D = Pillar-to-diameter ratio. Pillar width is taken as the minimum salt web thickness between two caverns.

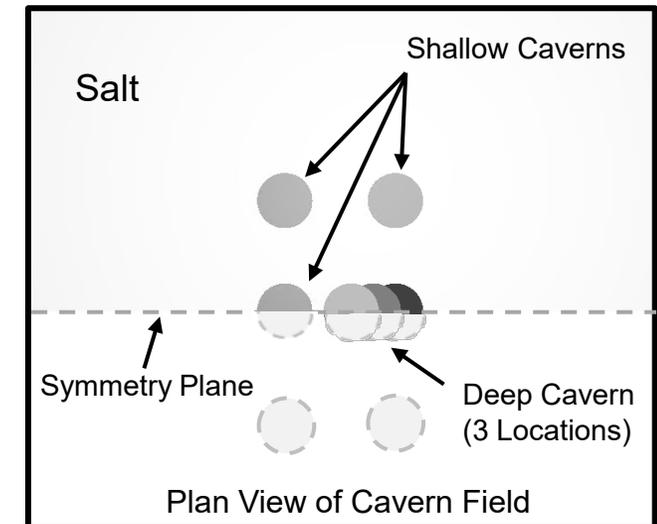
3D NUMERICAL MODEL - CAVERNS

› Deep cavern

- / Roof depth, 3,500 ft (1,067 m)
- / Final production casing seat at 3,350 ft
 - » 150 ft (46 m) above the roof of the new cavern
 - » 300 ft (91 m) below the floor of the nearby shallow cavern
- / 3 spacings from the nearby shallow cavern
 - » P:D = 0.2, 0.6, 1.0
 - » Well-to-cavern distances of 105 ft (32 m), 165 ft (50 m), and 225 ft (69 m)

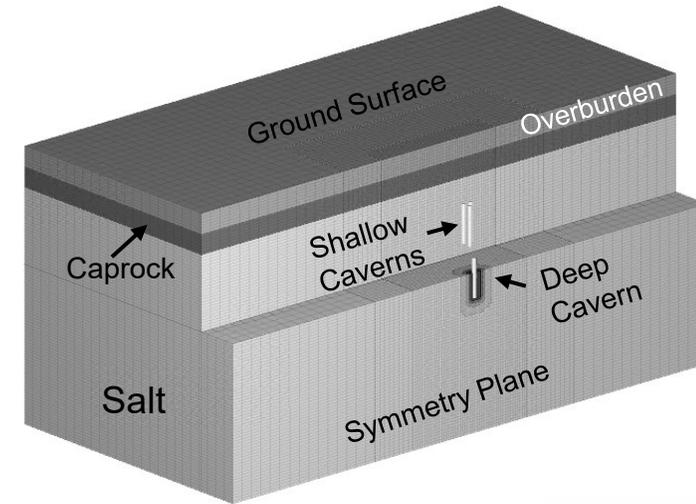


› 20 years of creep deformation is simulated prior to development of the deeper cavern



3D NUMERICAL MODEL - MATERIALS

- › Overburden and caprock were modeled as elastic materials
 - / Mechanical response has lesser impact on the well casing
- › Rock salt was modeled as a viscoplastic (creeping) material
 - / Two-component, power law used to model the steady-state creep behavior of the salt



Isometric View with Cut-Away

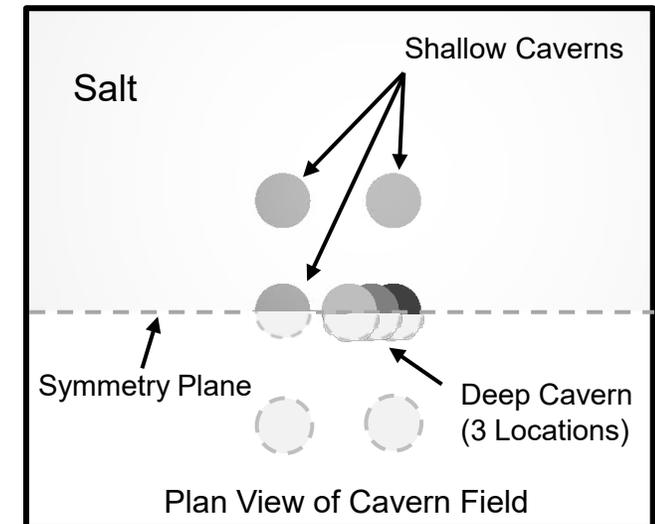
$$\dot{\varepsilon}_{vp} = A_1 \exp\left(\frac{-Q_1}{RT}\right) (\sigma_e)^{n_1} + A_2 \exp\left(\frac{-Q_2}{RT}\right) (\sigma_e)^{n_2}$$

$\dot{\varepsilon}_{vp}$ = viscoplastic strain rate

T = absolute temperature

σ_e = effective stress

$A_1, A_2, Q_1/R, Q_2/R, n_1,$ and n_2 = material properties.

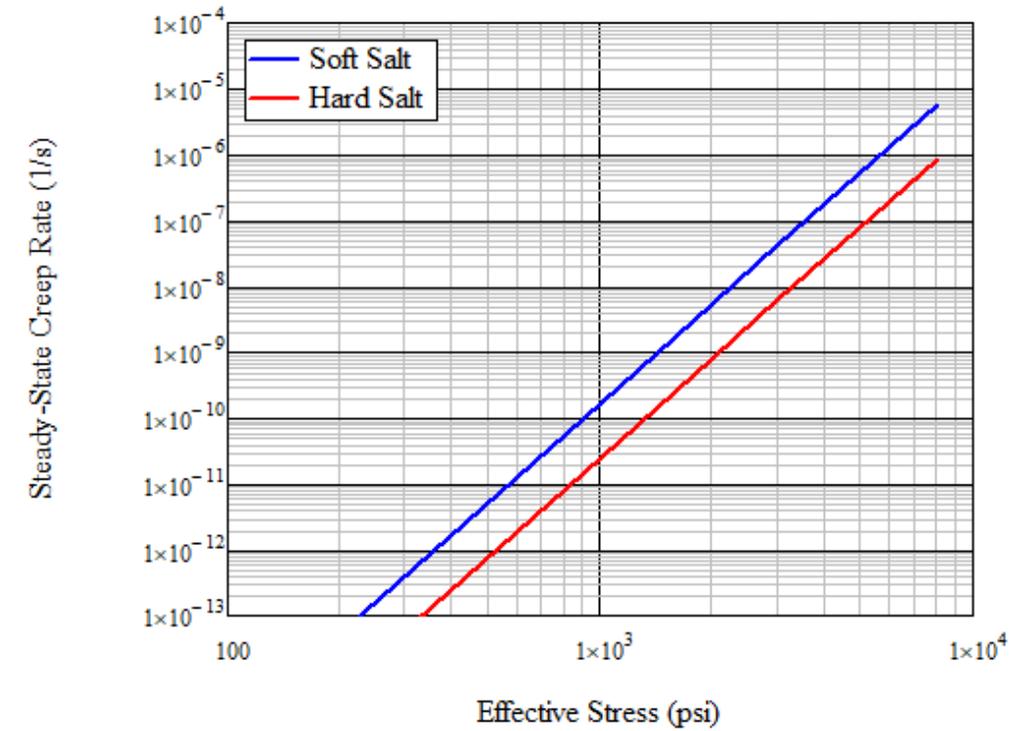


3D NUMERICAL MODEL - MATERIALS

Assumed Salt Creep Properties

- / Munson [1998] Soft and Hard salt
- / Almost an order of magnitude difference in creep rate

Parameter	Units	Soft Salt	Hard Salt	Overburden	Caprock
A_1	yr ⁻¹	3.096×10^{30}	4.560×10^{29}	—	—
A_2	yr ⁻¹	3.572×10^{20}	5.261×10^{19}	—	—
Q_1/R	R (K)	22,660 (12,589)	22,660 (12,589)	—	—
Q_2/R	R (K)	9,064 (5,036)	9,064 (5,036)	—	—
n_1	—	5.5	5.5	—	—
n_2	—	5.0	5.0	—	—
E	ksi (GPa)	2,940 (31)	2,940 (31)	435 (3)	8,720 (60)
ν	—	0.25	0.25	0.24	0.21
ρ	lbm/ft ³ (kg/m ³)	135 (2,162)	135 (2,162)	144 (2,307)	170 (2,723)



3D NUMERICAL MODEL - CASING

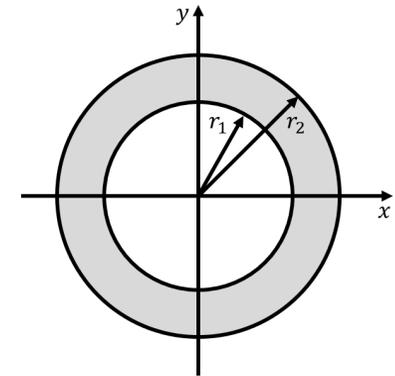
Final production casing of the deeper well

- / Assumed to be a 24-inch casing per API 5L [2018]
- / Nominal 1-inch wall thickness

Represented in the numerical model by structural beam, finite elements

- / Assigned circular-pipe, cross-sectional characteristics

Parameter	Units	Production Casing
Outside Diameter, d_o	in (cm)	24.0 (61)
Wall Thickness, t	in (cm)	1.00 (2.54)
Cross-Sectional Area, A_{cs}	in ² (cm ²)	72.3 (466)
Second Moment of Inertia, $I_y = I_x$	in ⁴ (cm ⁴)	4.79×10^3 (1.99×10^5)
Polar Moment of Inertia, J	in ⁴ (cm ⁴)	9.57×10^3 (3.99×10^5)
Young's Modulus, E	ksi (GPa)	29,000 (200)
Poisson's Ratio, ν	—	0.30
Mass Density, ρ	lbm/in ³ (g/cm ³)	0.284 (7.861)
Weight per Unit Length, W_c	lbf/ft (N/m)	246 (3,954)



Circular-Pipe, Cross-Section Schematic

$$A_{cs} = \pi \left(\frac{d_o}{2} \right)^2 - \pi \left(\frac{d_i}{2} \right)^2$$

$$I_x = I_y = \frac{\pi}{4} (r_2^4 - r_1^4)$$

$$J = \frac{\pi}{32} (d_o^4 - d_i^4)$$

A_{cs} = cross-sectional area of casing (in²)

d_o = outside diameter (in)

d_i = inside diameter (in)

$I_{x,y}$ = area moment of inertia about the x- and y-axes (in⁴)

$r_{1,2}$ = inner and outer radii (in)

J = polar moment of inertia (in⁴).

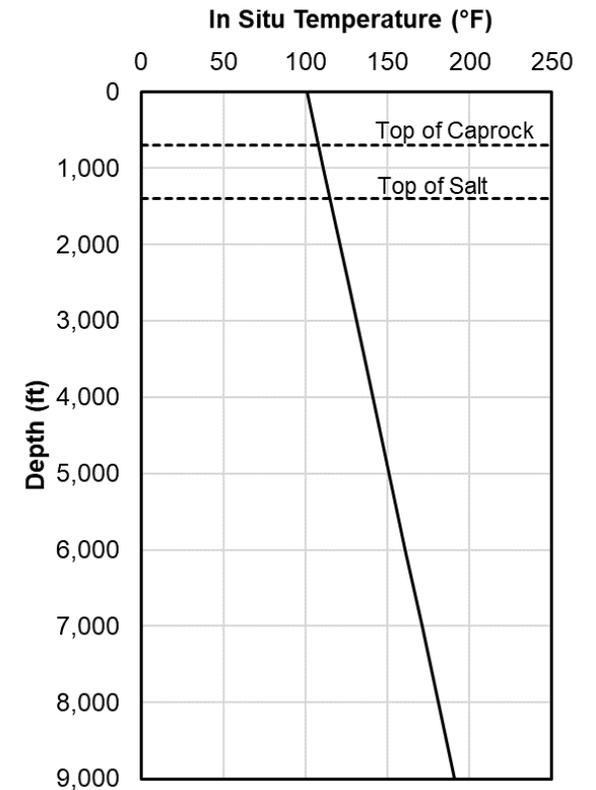
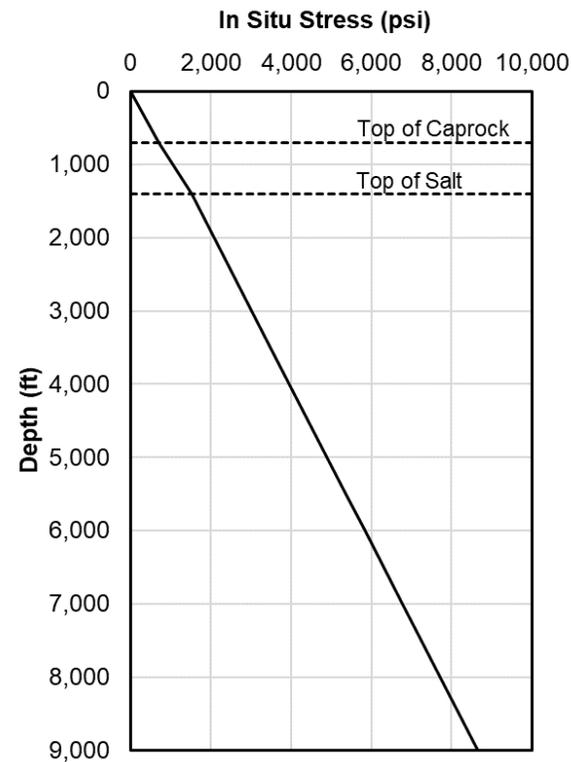
3D NUMERICAL MODEL – IN SITU CONDITIONS

› In Situ Stress

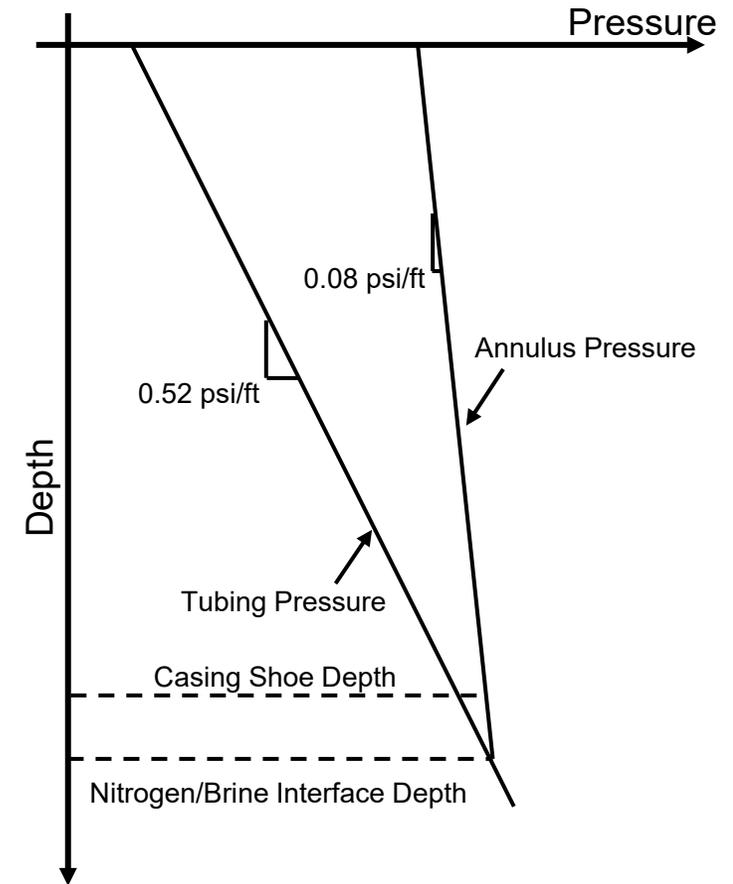
- / Assumed to be lithostatic & isotropic
- / Equal to weight of overburden
- / Vertical = Horizontal stresses

› Geothermal Gradient

- / Modeled as a linear profile
 - » 100°F at ground surface, increasing by 1°F per 100 ft of depth



- › Brine-filled pressure conditions inside the caverns
 - / Conservative (low-pressure) condition for liquids storage
 - / Saturated brine weight density of 75 lb/ft^3
 - » 0.52 psi/ft pressure gradient
- › Nitrogen Mechanical Integrity Test (MIT) conditions
 - / Assumed wellhead annulus pressure of $2,419 \text{ psi}$
 - / Nitrogen weight density of 11.22 lb/ft^3
 - » Density of nitrogen at $2,400 \text{ psi}$ and 80°F
 - » 0.80 psi/ft pressure gradient at the casing shoe depth



Schematic of Well Pressures During a Nitrogen MIT

- › Multiple sources of loading contribute to the total stress state in the casing, including,
 - / Casing buoyant weight
 - / Internal fluid pressure
 - / External formation pressure
 - / Formation movement (salt creep)
 - / Bending during installation in a deviated wellbore
 - / Thermal expansion & contraction

- › Several loading conditions are simplified or neglected for this study

› Casing buoyant weight

- / During installation, the casing hangs from the wellhead, resulting in a vertical distribution of axial tensile loading that decreases with depth
- / Drilling fluid or cement in the wellbore provide buoyancy forces (opposing the hanging weight) that increase with depth
 - » Assumed the cement has a density equal to 10 lb/gal drilling mud
- / Resulting axial stress is most tensile at the wellhead, and becomes compressive near the casing shoe depth

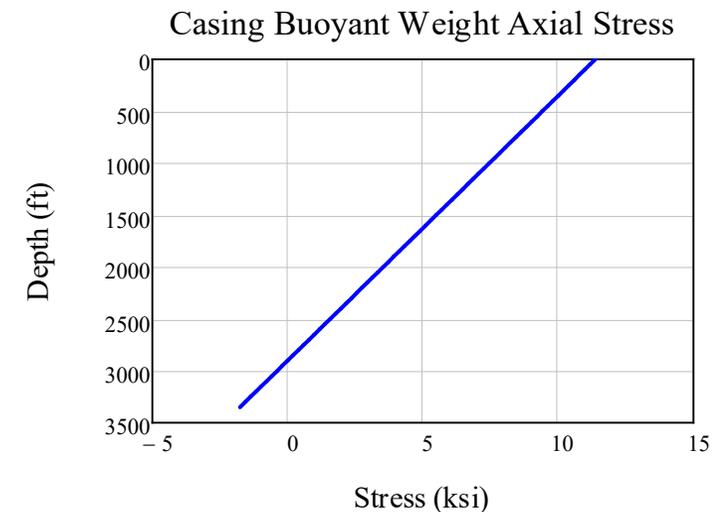
$$\sigma_w = \frac{4}{\pi(d_o^2 - d_i^2)} \times [W_c (D_{cs} - Z) - W_m (z)]$$

W_c = weight of the casing (lb/ft)

W_m = weight of the mud (lb/ft)

D_{cs} = depth of the case shoe (ft)

z = depth below the wellhead (ft).



WELL CASING LOADS – INTERNAL PRESSURE

› Internal fluid pressure

- / Assumed nitrogen MIT pressure conditions
 - » 0.80 psi/ft at the casing shoe depth
- / Imposes a compressive radial stress in the casing
 - » Equal to the nitrogen pressure at the inner surface
- / Imposes a tensile tangential (hoop) stress in the casing
 - » Significant (30 ksi at depth)

Radial Stress at Inner Surface

$$\sigma_r^{IP} = P_{wha} + \gamma_{N_2} (z)$$

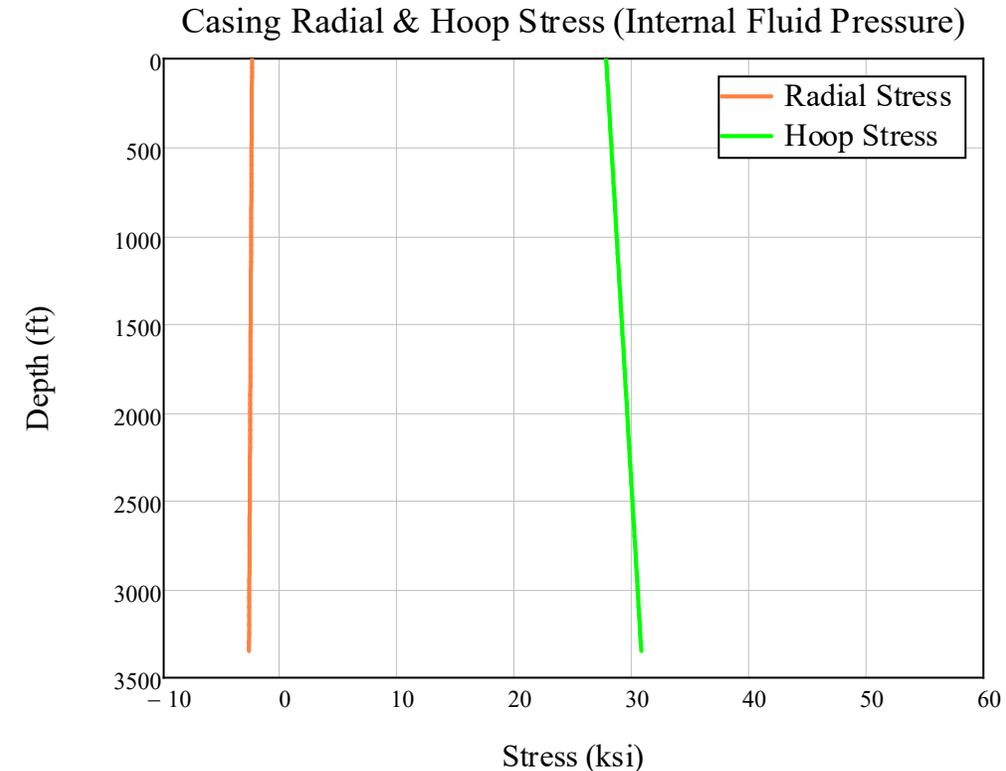
P_{wha} = annulus pressure at the wellhead (psi)

γ_{N_2} = nitrogen weight density at MIT pressure and temperature (lb/in³)

z = depth below the wellhead (in).

Hoop Stress at Inner Surface

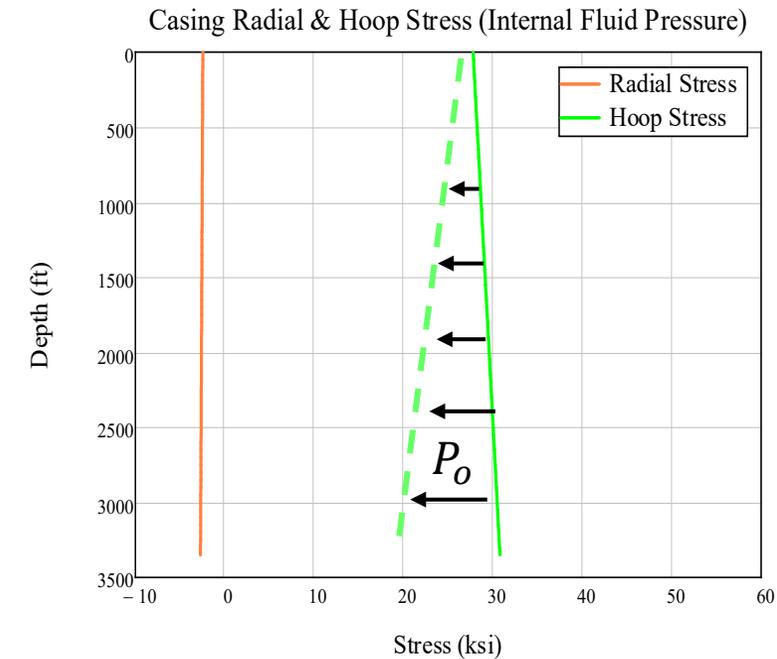
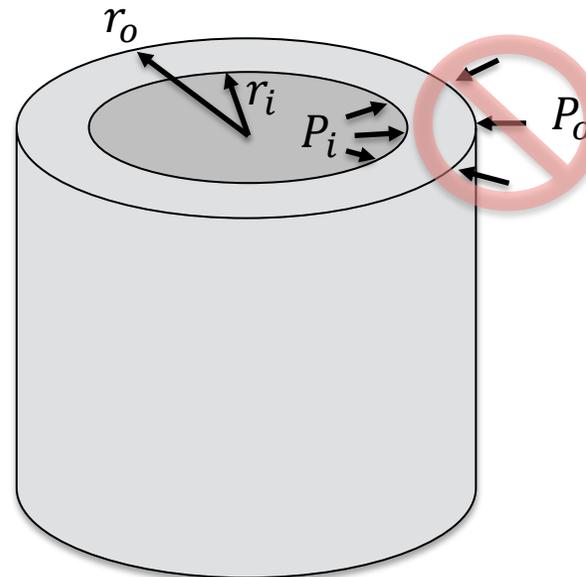
$$\sigma_\theta^{IP} = -\sigma_r^{IP} \frac{(d_o^2 + d_i^2)}{(d_o^2 - d_i^2)}$$



WELL CASING LOADS – EXTERNAL PRESSURE

External formation pressure

- / Provides a confining pressure on the outside surface of the casing (P_o)
- / Imposes a compressive radial stress in the casing
 - » Equal to the formation pressure at the outer surface
- / Imposes a compressive tangential (hoop) stress in the casing
 - » Opposes (reduces) the tensile hoop stress imposed by the internal fluid pressure
- / The beneficial effects of an external confining pressure are conservatively neglected in this study



WELL CASING LOADS — FORMATION MOVEMENT

› Formation movement (salt creep)

- / Creep deformation will impart axial, bending, and shear stresses in the casing
- / The shear stresses in this application are significantly smaller—neglected
- / The maximum bending stress occurs at the outer surface (diameter)
- / Bending stress is compressive on the inside of the bend, and tensile on the outside of the bend

Creep-Induced Axial Stress

$$\sigma_A = \frac{F_A}{A_{cs}}$$

F_A = axial force (lb_f)

A_{cs} = cross-sectional area of casing (in²).

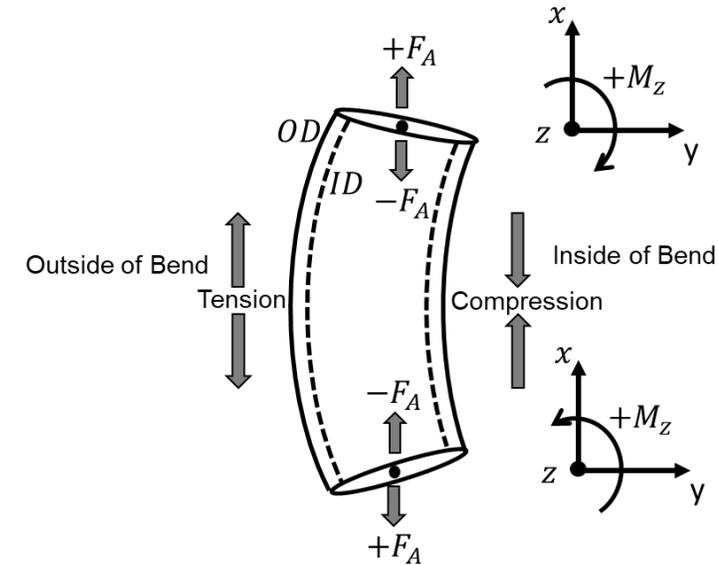
Creep-Induced Bending Stress

$$\sigma_B = \frac{Mc}{I}$$

M = bending moment (in-lbs)

c = casing radius (in)

I = area moment of inertia about the axes perpendicular to the pipe centerline (in⁴).



WELL CASING LOADS – INSTALLATION & THERMOMECHANICAL

› Bending during installation in a deviated wellbore

- / If installed in a wellbore that deviates from vertical, bending stresses will develop
- / Combined bending loading from a deviated well and creep deformation is dependent on relative orientation (i.e., site-specific)
- / Assumed a perfectly vertical wellbore for this study

› Thermal expansion & contraction

- / Fluid injection and withdrawal will induce thermal gradients, imposing thermomechanical loading
- / DeVries et al. [2007] found the thermomechanical effects are minor in comparison to loading imposed by formation movement (salt creep)
- / Thermal expansion & contraction are neglected in this study

WELL CASING STRESSES

- › The total stress state is estimated for the casing loads considered
- › Vertical stress is the summation of the casing buoyant weight and the creep-induced axial and bending stresses
- › Radial stress is equal to the nitrogen pressure
- › Hoop stress is attributable to the internal fluid (nitrogen) pressure
- › These are taken to be the principal stresses

$$\sigma_z = \sigma_w + \sigma_A + \sigma_B$$

$$\sigma_r^{IP} = P_{wha} + \gamma_{N_2}(z)$$

$$\sigma_\theta^{IP} = -\sigma_r^{IP} \frac{(d_o^2 + d_i^2)}{(d_o^2 - d_i^2)}$$

- › Well casing design typically accounts for multiple load cases and failure modes, including,
 - / Burst (internal pressure)
 - / Collapse (external pressure)
 - / Tension
 - / Compression (buckling or crippling)
 - / Triaxial yield

- › The von Mises effective stress is a convenient measure of the triaxial stress state

- › Evaluate the potential for material yield under the considered loading conditions

WELL CASING FAILURE — FACTORS OF SAFETY

- › Factor-of-safety (FS) values with respect to casing yield are calculated

$$FS_y = \frac{\sigma_y}{\sigma_e}$$

σ_y = yield strength

$$\sigma_e = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}, \text{ von Mises effective stress}$$

$\sigma_1, \sigma_2, \sigma_3$ = principal stresses.

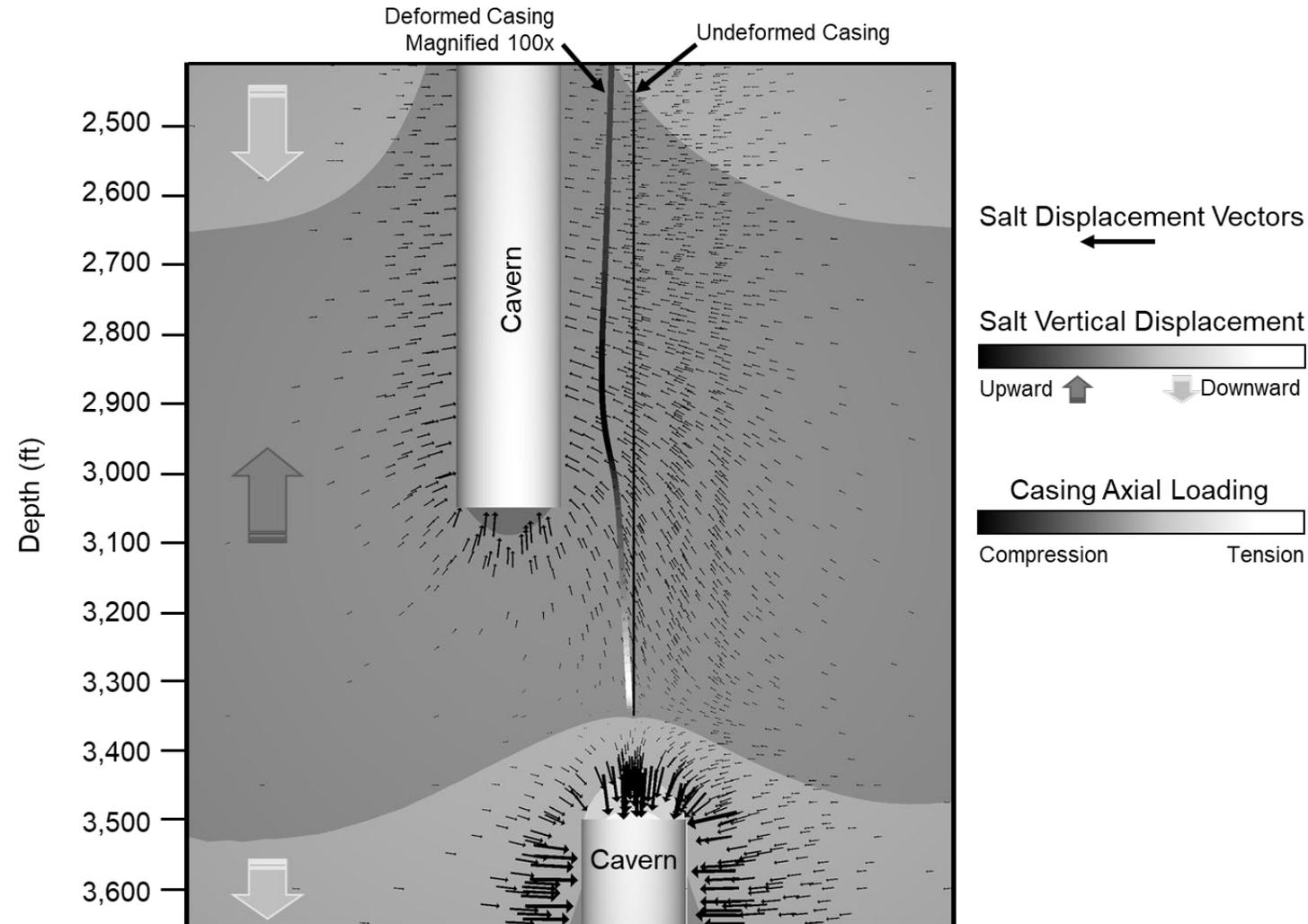
- › Casing failure (yield) is predicted when the von Mises effective stress exceeds the yield strength

$$FS_y \leq 1.0$$

- › Similar FS values can be calculated with respect to ultimate failure (rupture)

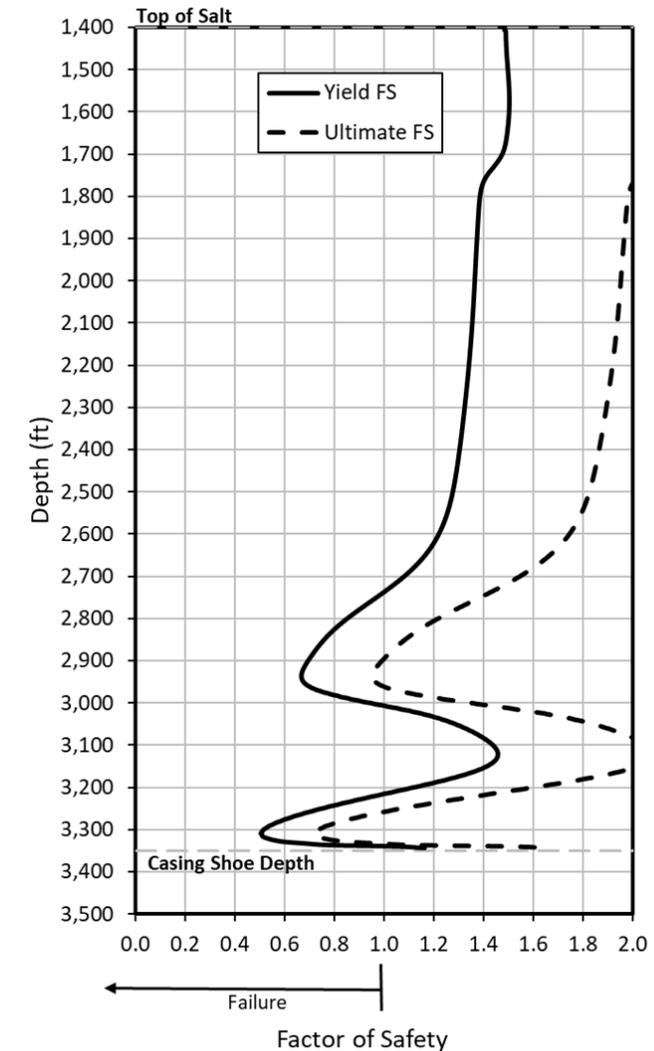
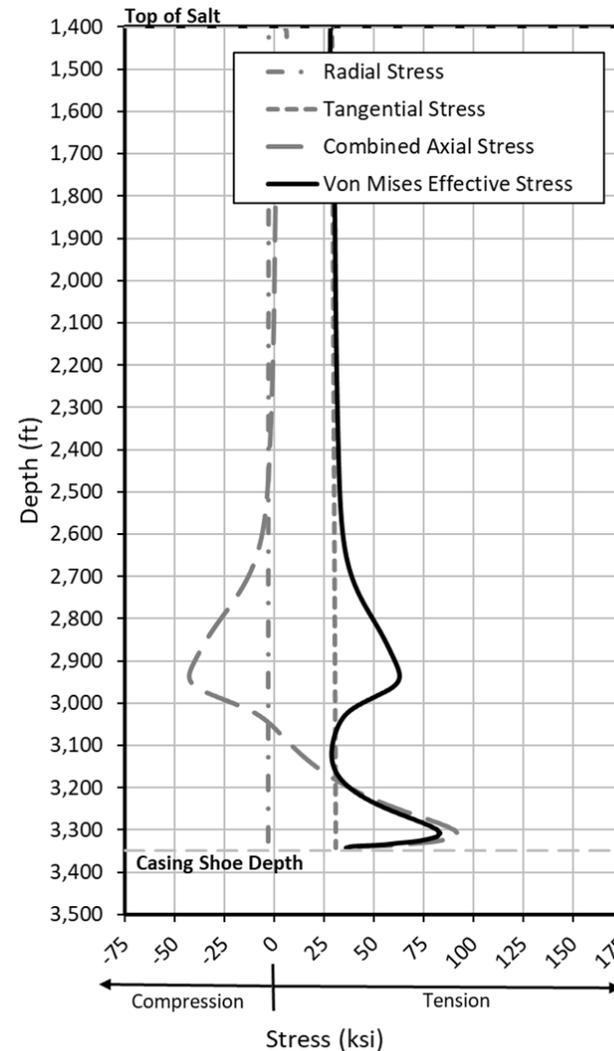
MODELING RESULTS

- › **General creep-induced deformation predicted by the numerical modeling**
 - / Shown for Soft salt and 105 ft (32 m) well-to-cavern spacing
- › **Nearby cavern creep closure causes,**
 - / High compression loading in the casing
 - » Around 2,900 ft
 - / Moderate bending loading in the casing
- › **Extensional loading near the shoe**
 - / Expected (typical) near roof of cavern
 - / Amplified here because of the upward creep movement in the floor of the nearby cavern



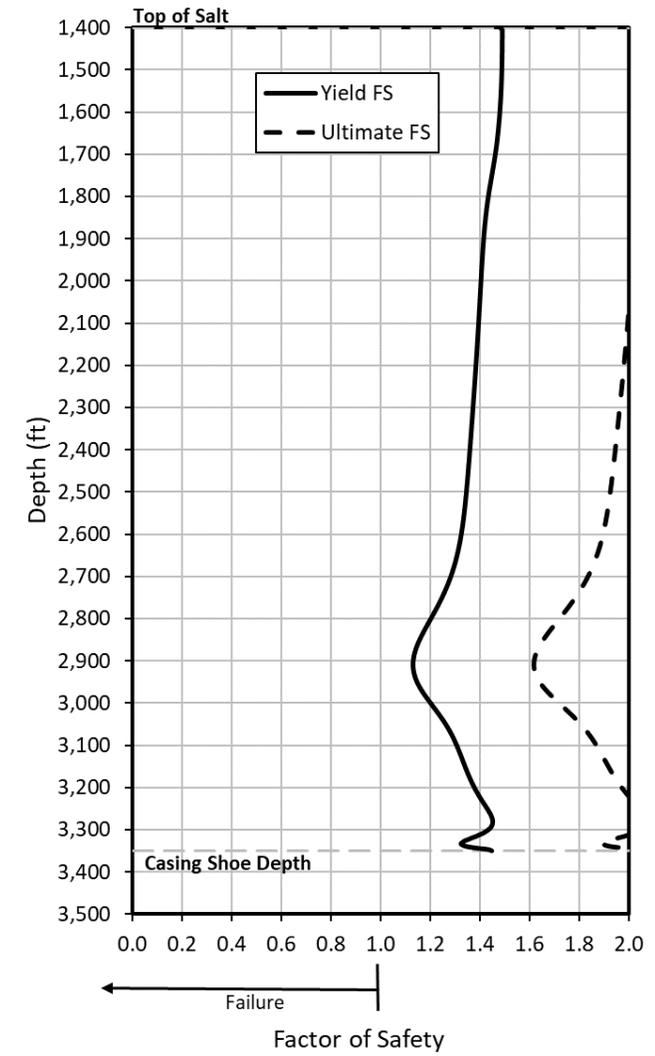
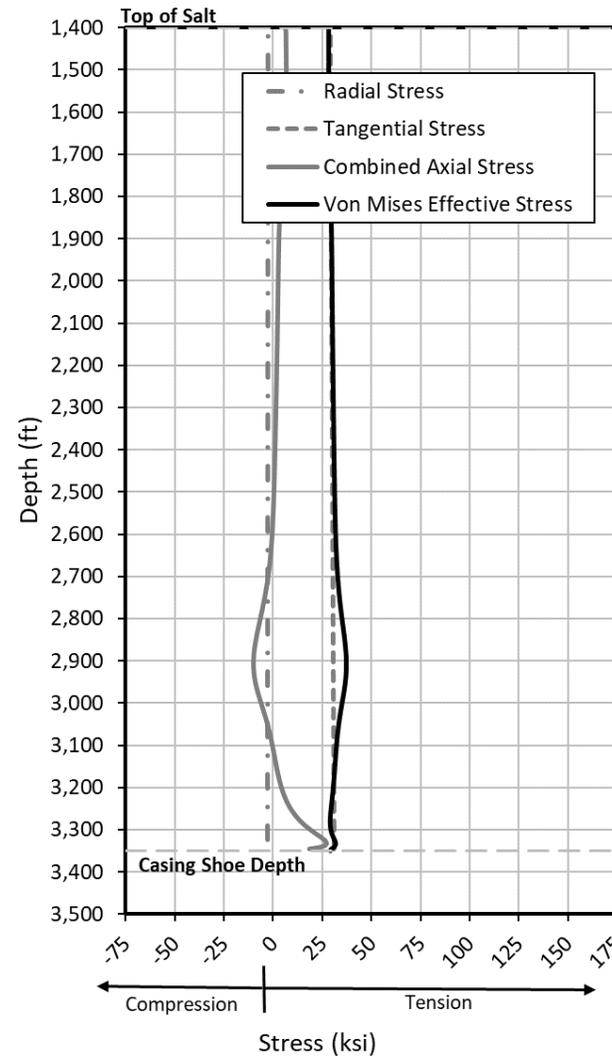
STRESS RESULTS

- › Radial & tangential (hoop) stress from nitrogen MIT pressure
- › Combined axial loading
 - / Superimposed the buoyant weight of the casing on the creep-induced axial loads
 - / Significant compressive axial loading around 2,950 ft
- › Assuming API Grade X42 casing to calculate FS values
 - / Minimum yield strength of 42 ksi (290 MPa)
 - / Casing is predicted to yield through an approximate 300 ft interval
 - / Casing is predicted to rupture around 2,950 ft



STRESS RESULTS

- General effect of creep rate and separation distance illustrated by scenario assuming Hard salt with a 225 ft well-to-cavern spacing
- Significant reduction in predicted casing stresses and higher FS values
 - API X42 casing



RESULTS SUMMARY

- › Summary results for the three well-to-cavern separation distances considered assuming Soft and Hard salt creep properties
 - / Results taken from the salt above a depth of approximately 3,100 ft (above the high-tensile region)
 - / FS values calculated assuming API Grade X42 casing

- › Small gains from increased well-to-cavern separation distance

- › Significant effect from salt creep rate
 - / Hard Salt – slow creeping
 - / Soft Salt – fast creeping

Salt Type	Well-to-Cavern Separation Distance ft (m)	Maximum Effective Stress ksi (MPa)	Minimum FS _y —	Reduction in Maximum Effective Stress Percent
	105 (32)	63 (435)	0.67	(baseline)
Soft Salt	165 (50)	60 (415)	0.70	5%
	225 (69)	57 (393)	0.74	10%
Hard Salt	105 (32)	39 (267)	1.09	39%
	165 (50)	38 (262)	1.11	40%
	225 (69)	37 (257)	1.13	41%

CONCLUSIONS

- › Well casing design for storage caverns to be developed beneath existing caverns should consider creep-induced loading
- › Among the casing loads considered in this study, creep-induced axial stresses and internal fluid pressure-induced hoop stresses were dominant
- › Increasing the well-to-cavern spacing has minimal effect on the predicted casing deformation
- › Salt creep rate has a significant effect on the potential for casing damage
 - / Site-specific characterization of the creep behavior is necessary
- › The complex geometry of real caverns of varying size, shape, and spacing could have a significant effect on the predicted creep-induced casing deformation
 - / Site-specific analyses are necessary to assess the potential for creep-induced damage
- › Bending stresses induced by installation of the casing in a deviated wellbore will affect the total stress state in the casing

THANK YOU!



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