SAND2021-11074C

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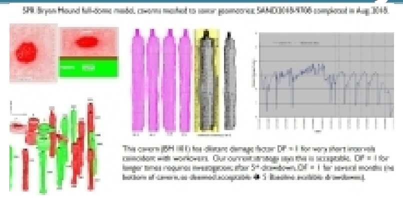
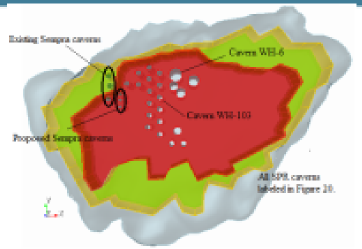
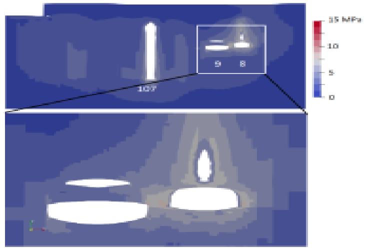
Effect of the Addition of a Low Equivalent Stress Creep Mechanism to the Analysis of Geomechanical Behavior of the SPR West Hackberry Site







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SMRI Fall 2021 Technical Conference

20-21 September 2021

Galveston, Texas, USA

U.S. DEPARTMENT OF ENERGY NNSA

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Presentation Overview

- Purpose of using salt creep constitutive models in geomechanical analyses
- Overview of the Strategic Petroleum Reserve (SPR) West Hackberry (WH) Site
- Computation mesh analyses of the full-dome model
- Traditional Munson-Dawson (M-D) steady-state creep model
- Summary of the 2015 analysis using M-D creep model
- Extended M-D model with addition of creep at low equivalent stresses
- Comparison of 2015 M-D creep model versus 2020 extended M-D creep model
- Potential impacts on analytical results, influence on cavern operations
- Conclusions

Why do we model salt creep in geomechanical models?

Salt deforms (creeps) under equivalent (deviatoric) stress conditions (i.e., oil pressure in caverns not equal to in situ pressure in salt).

Salt creep causes storage caverns to deform inward, thus losing volume.

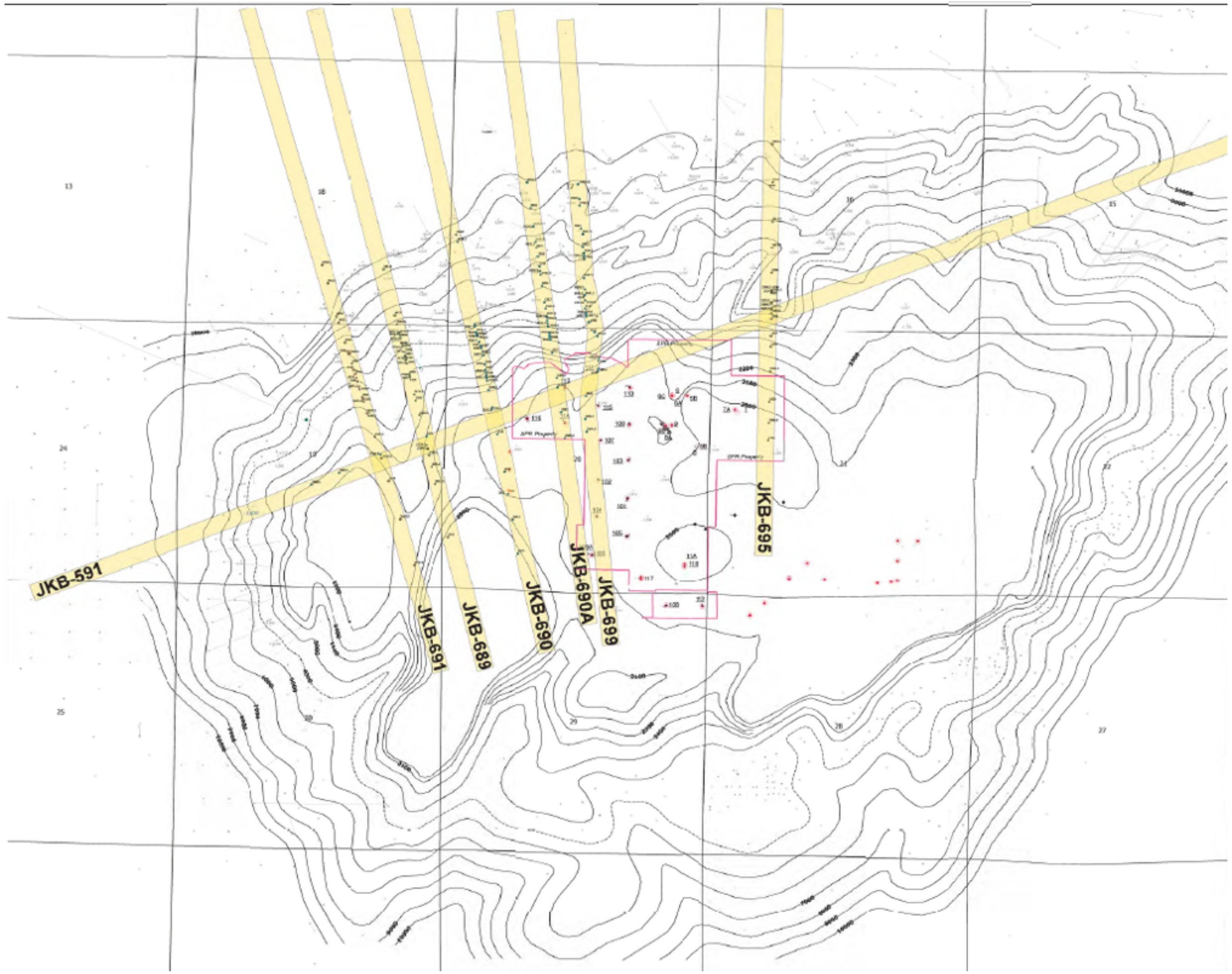
Loss of volume affects salt above, around caverns, putting stresses and strains on borehole casings.

Loss of volume also translates to surface subsidence, affecting surface infrastructure. SO……

Accurate evaluation of salt creep behavior drives decisions about cavern operations.

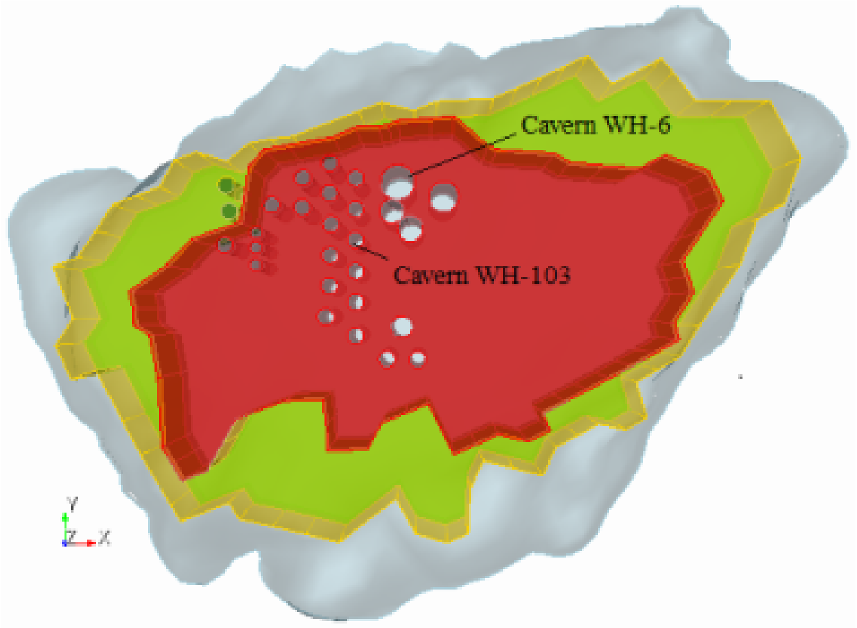
Sandia Labs has historically used Munson-Dawson creep model for salt for geomechanical analyses of U.S. Strategic Petroleum Reserve oil storage sites.

West Hackberry (WH) SPR Site



- West Hackberry salt dome in southwestern Louisiana
- ~228 MMB of oil storage in 21 caverns.
- 5 unusually-shaped, reasonably axisymmetric storage caverns (#6, 7, 8, 9, 11) built in 1940s-1950s.
- 17 cylindrical-shaped storage caverns (#101 -117) built in early 1980s.
- Approximately 480m sandstone overburden, 120 m anhydrite/ carbonate caprock over salt dome.
- WH salt is reasonably homogeneous, isotropic, relatively high creep

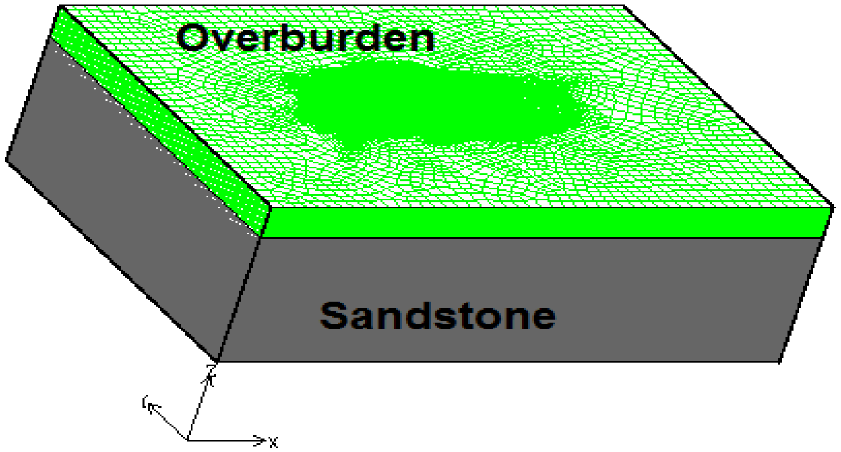
Full Dome Finite Element Model for West Hackberry Site

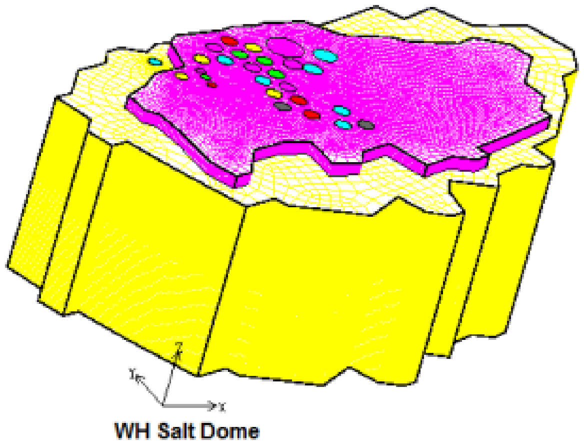


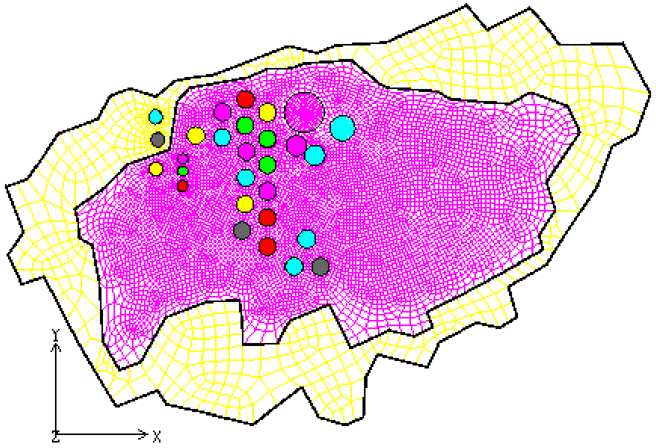
Contains entire WH salt dome, all 22 WH storage caverns

Full mesh contains 5.95 million elements

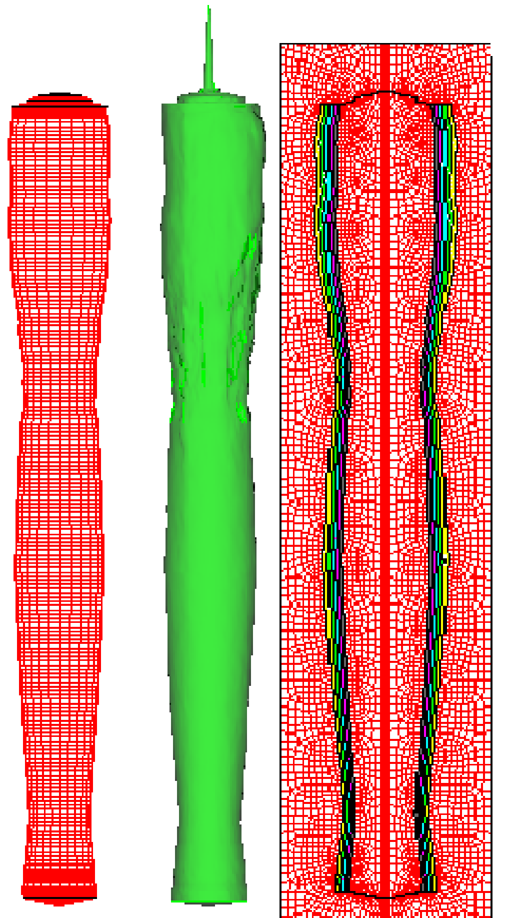
24,000' W-E X 18,000' N-S X 8,000' depth

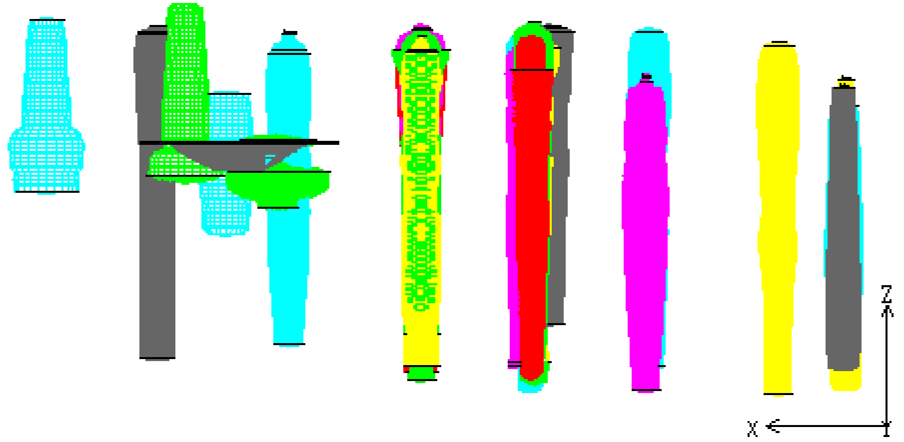


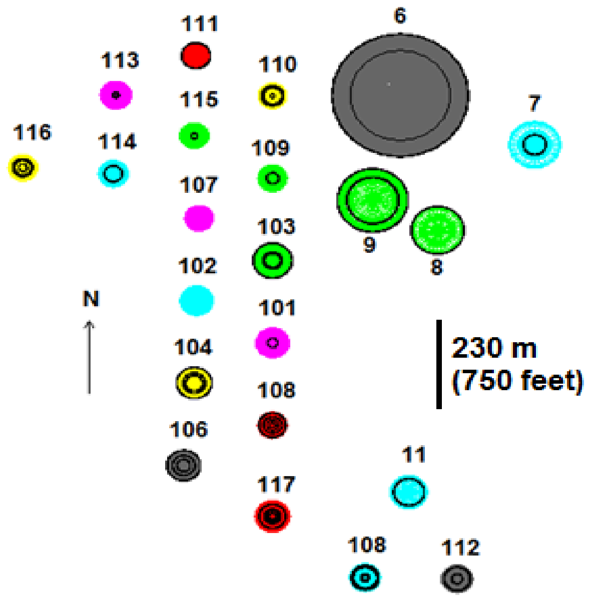


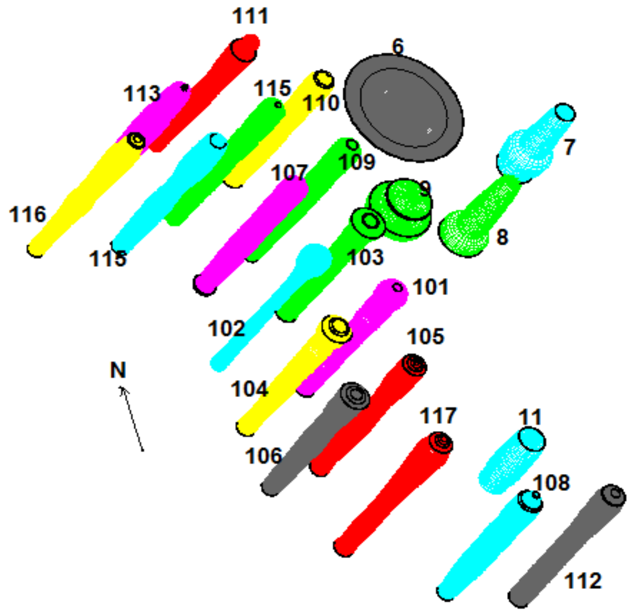


Full Dome Model for West Hackberry Site









All caverns meshed to sonar-based geometries – axisymmetric, based on area-averaged radius at each sonar depth

Up to 5 drawdown leach layers ("onion skins") included for all WH caverns

Traditional MD Steady-State Creep Model

- Traditional MD model (Munson-Dawson, based on Norton-Hoff model) has 3 steady-state creep mechanisms (1, 2, 3).

- 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.

- Coefficient A_2 determined from lab tests on salt core samples, but for field-scale simulations we usually add a multiplier to try to match subsidence & closure data.

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

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

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

Transient strain ε_t^* dominates during large pressure change activities; Coefficient K_0 also determined from lab tests, multiplier has been added to match field data.

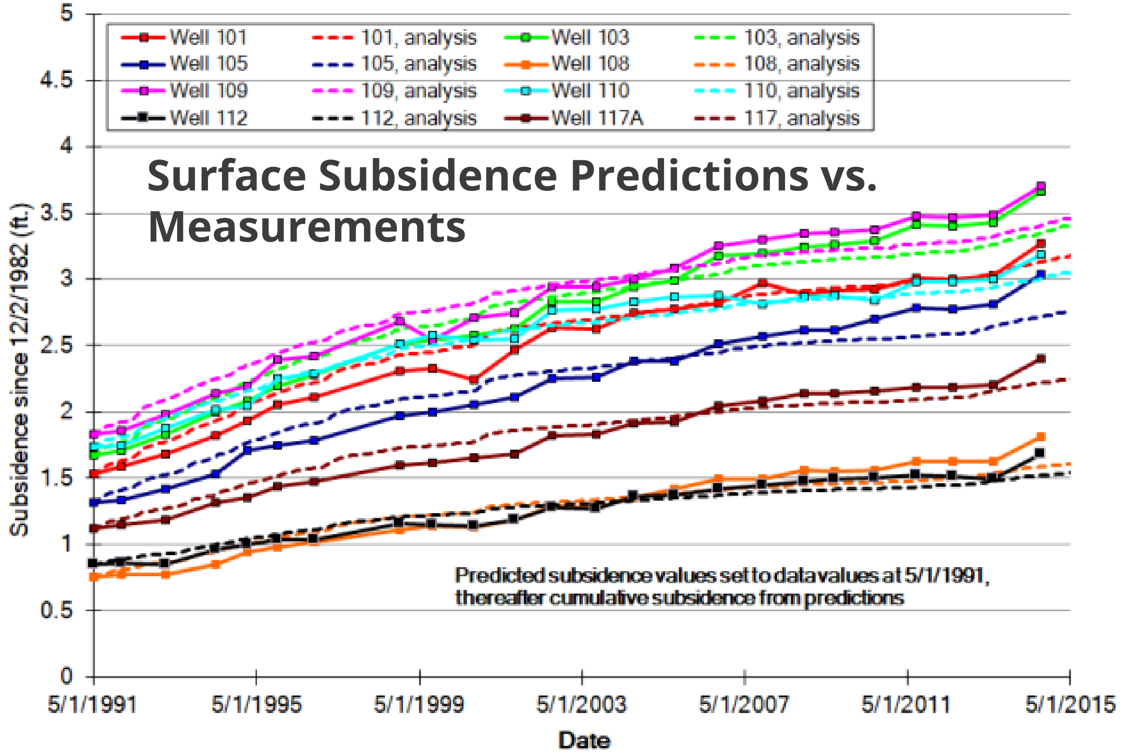
2015 Analysis Parameters for the M-D Creep Model

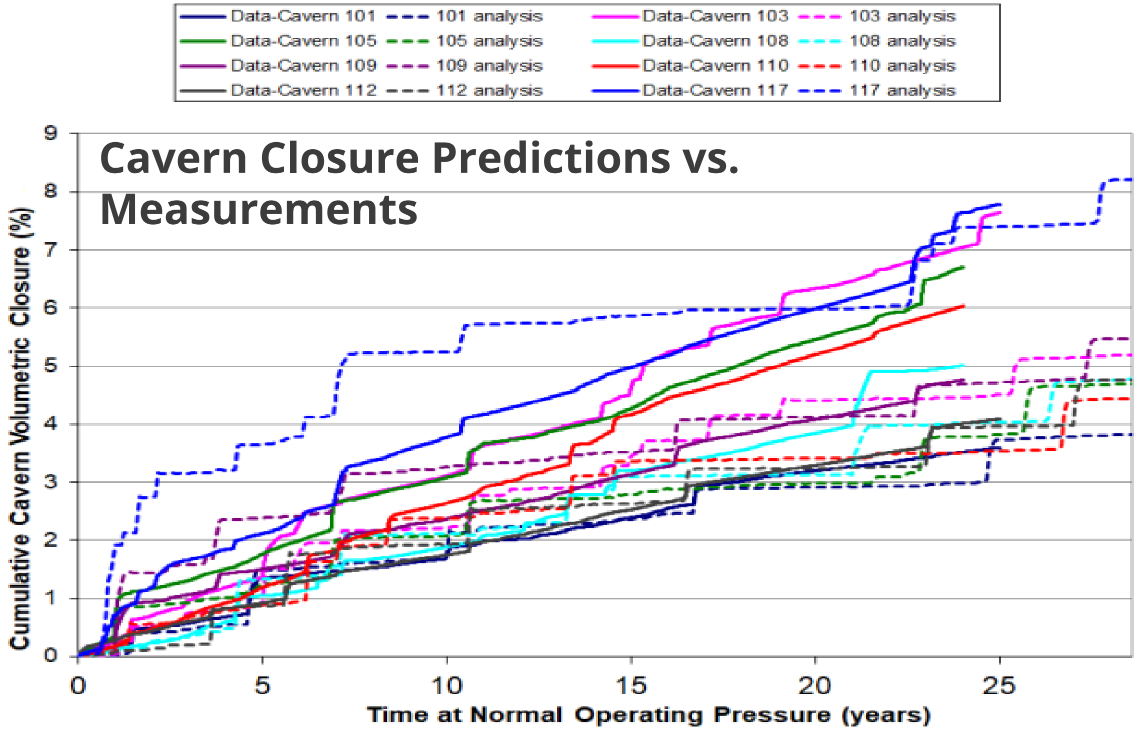
Property or parameter	Values
Primary Creep Constant $\mathbf{A_1}$, sec $^{-1}$	9.81×10^{22}
Exponent $\mathbf{n_1}$	5.5
$\mathbf{Q_1}$, cal/mol	25000
Secondary Creep Constant $\mathbf{A_2}$, sec $^{-1}$	1.13×10^{13}
Exponent $\mathbf{n_2}$	5.0
$\mathbf{Q_2}$, cal/mol	10000

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

Cavern	A_2 multiplication factor	Cavern	A_2 multiplication factor
101	1.44	112	1.21
102	2.44	113	1.77
103	2.08	114	1.43
104	1.79	115	1.51
105	2.79	116	3.20
106	1.48	117	1.73
107	2.24	6	1.44
108	1.73	7	1.67
109	1.46	8	0.89
110	2.35	9	1.96
111	2.42	11	1.21
WH Salt	1.80		
K_f, Multiplication factor for K_0 in transient creep equation (i.e., K_0 used in analysis = $(K_{0,\ Munson})$ * (K_f))			K_f=18.2

2015 Analysis using M-D Creep Model for West Hackberry Site

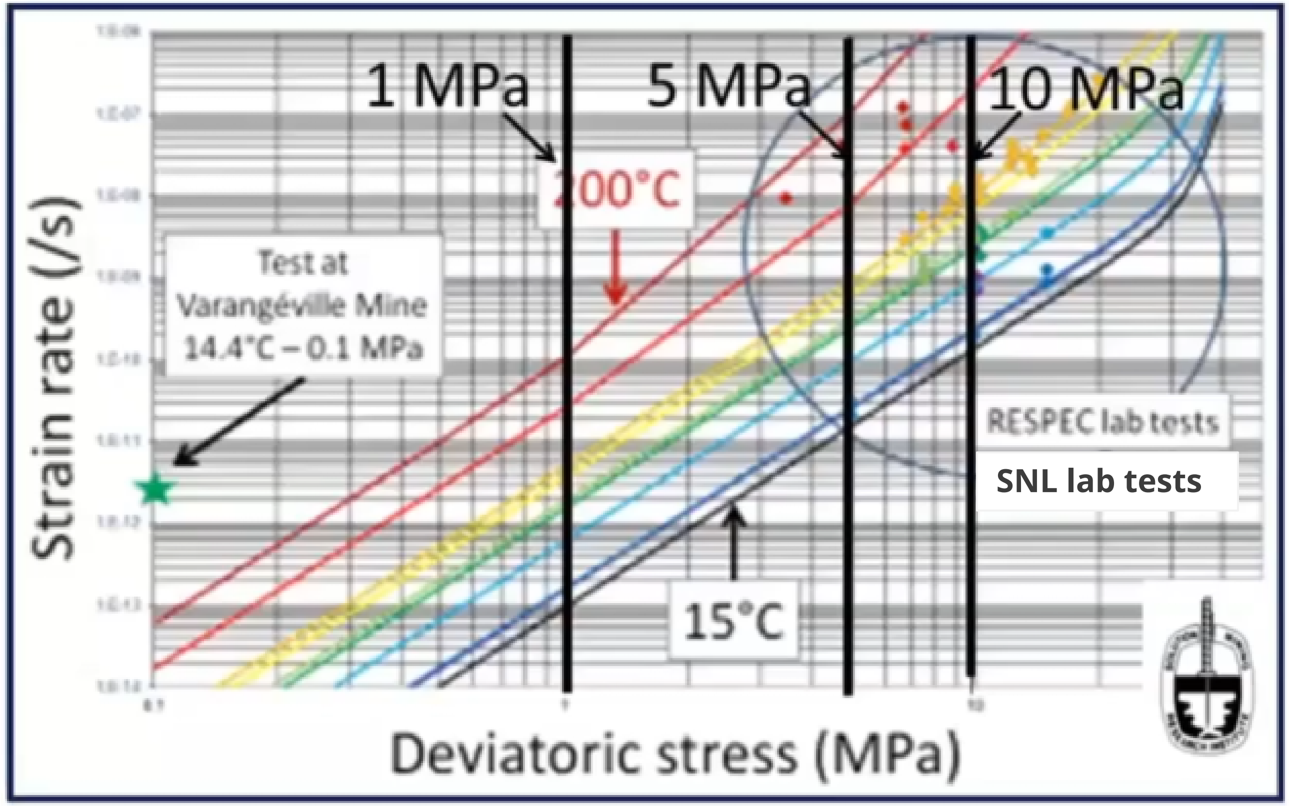




- M-D creep model with modified parameters is very effective at predicting surface subsidence.
- Model is not effective for predicting steady-state portion of cavern volume closure.

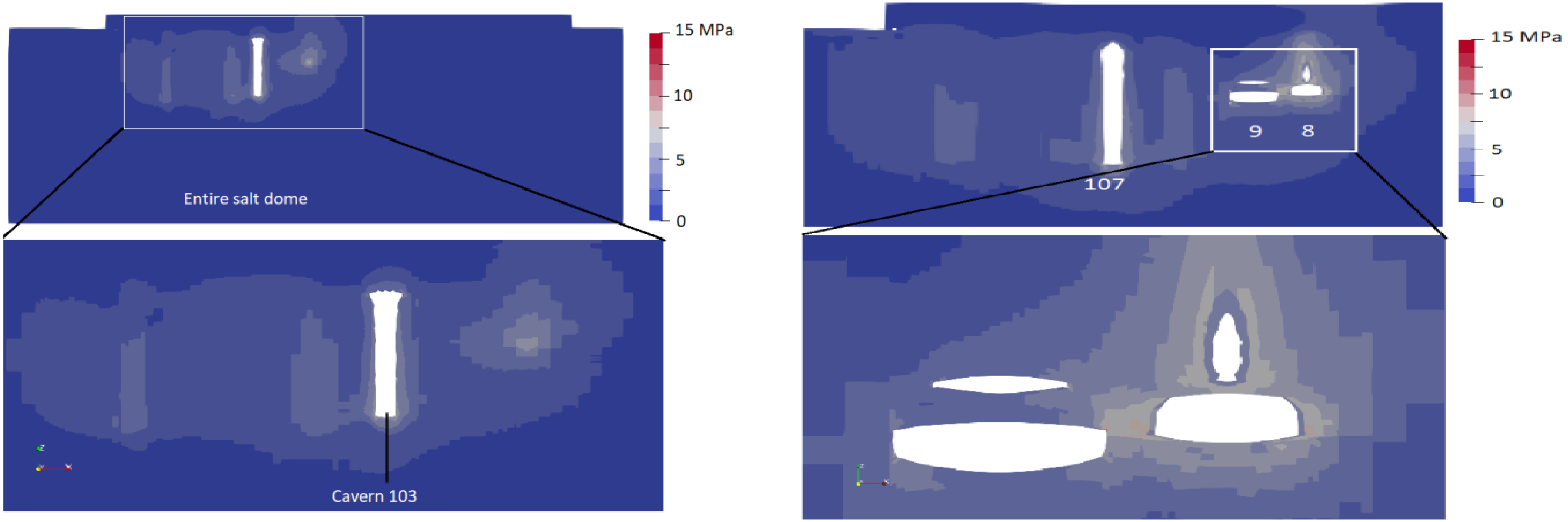
What are we missing?

- WIPP, other cavern modelers see same underprediction of closure.
- Most creep tests performed for stresses > 8 MPa.
- Recent research from US-German collaborative research, also Berest, Spiers show that there may be a mechanism at stresses < 8 MPa not captured by previous tests.
- Tests at 0.1-8 MPa are difficult because they are very slow (take months-years to run), very sensitive to small ΔT (<0.1C).



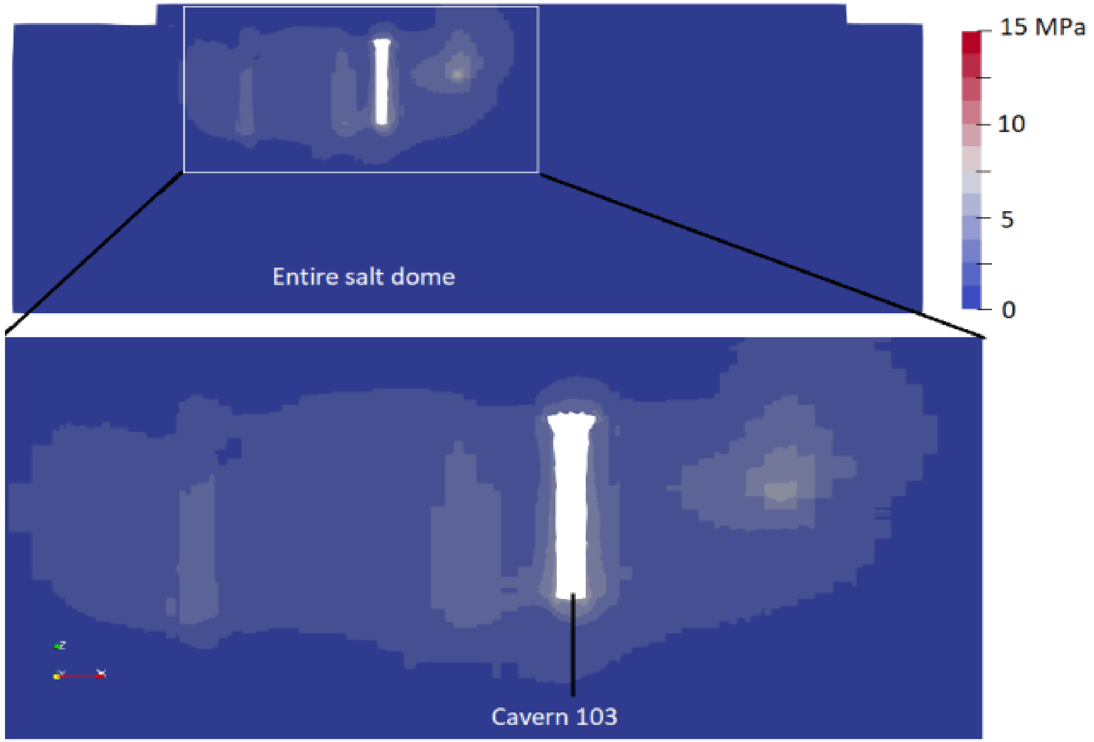
Berest et al., 2020

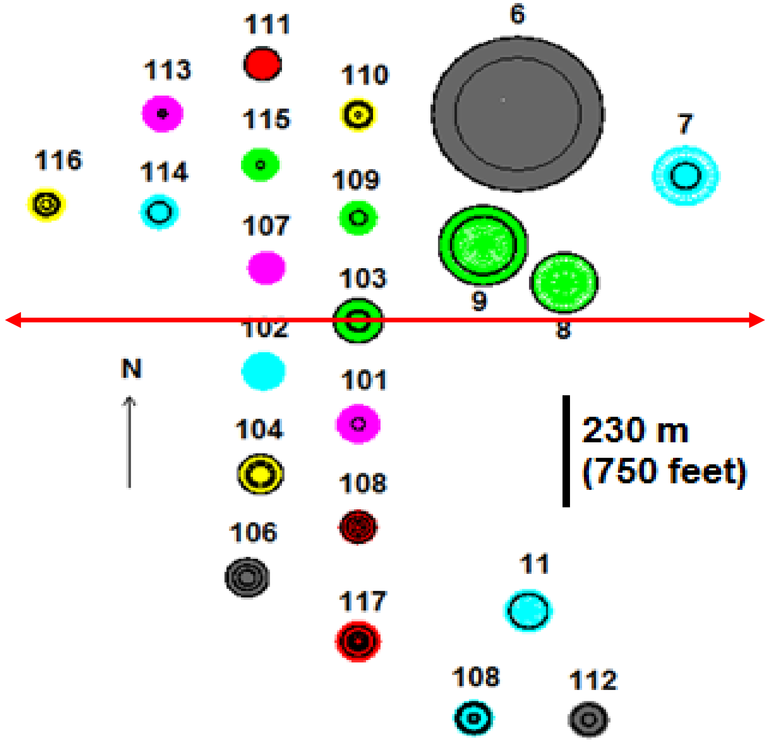
Low Equivalent Stress Creep - Why is it Important?



The volume of salt experiencing stress of 10 MPa or greater is significantly small compared to stress less than 10 MPa.

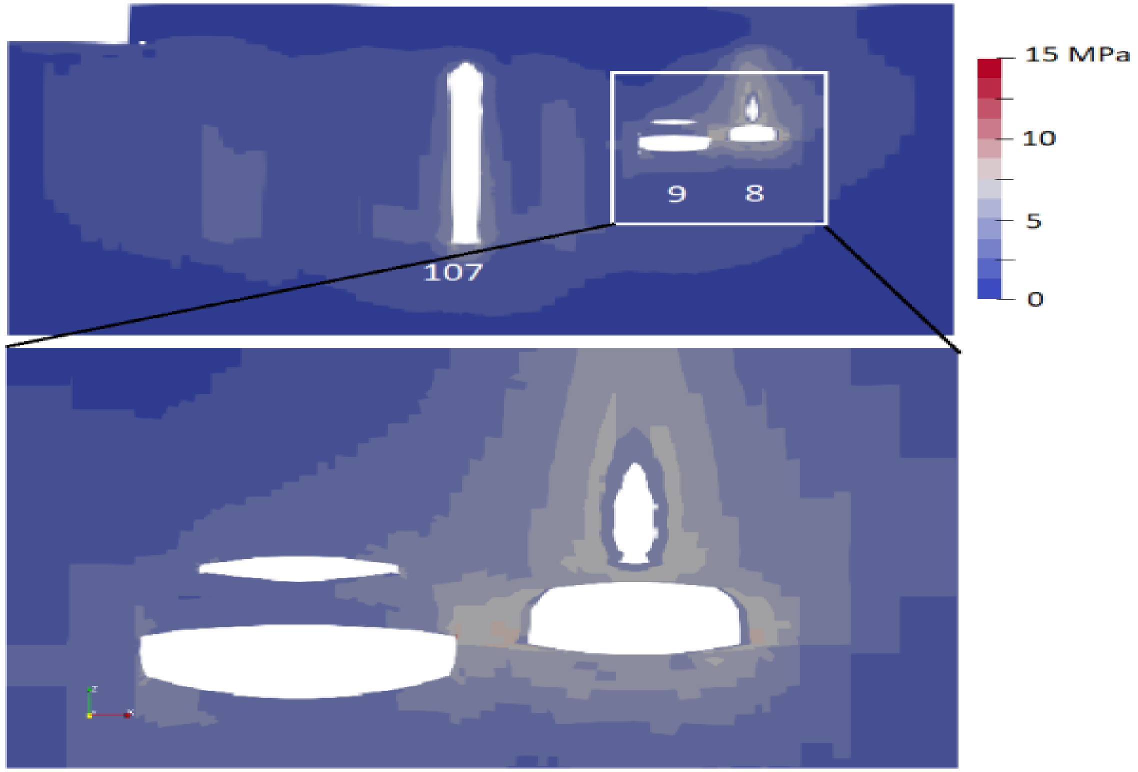
Low Equivalent Stress Creep - Why is it Important?

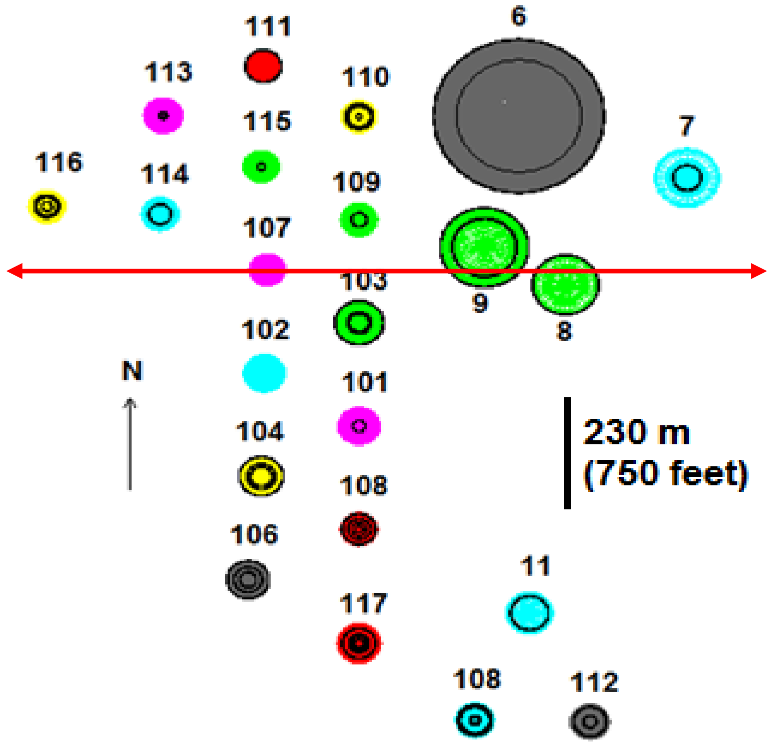




The volume of salt experiencing stress of 10 MPa or greater is significantly small compared to stress less than 10 MPa.

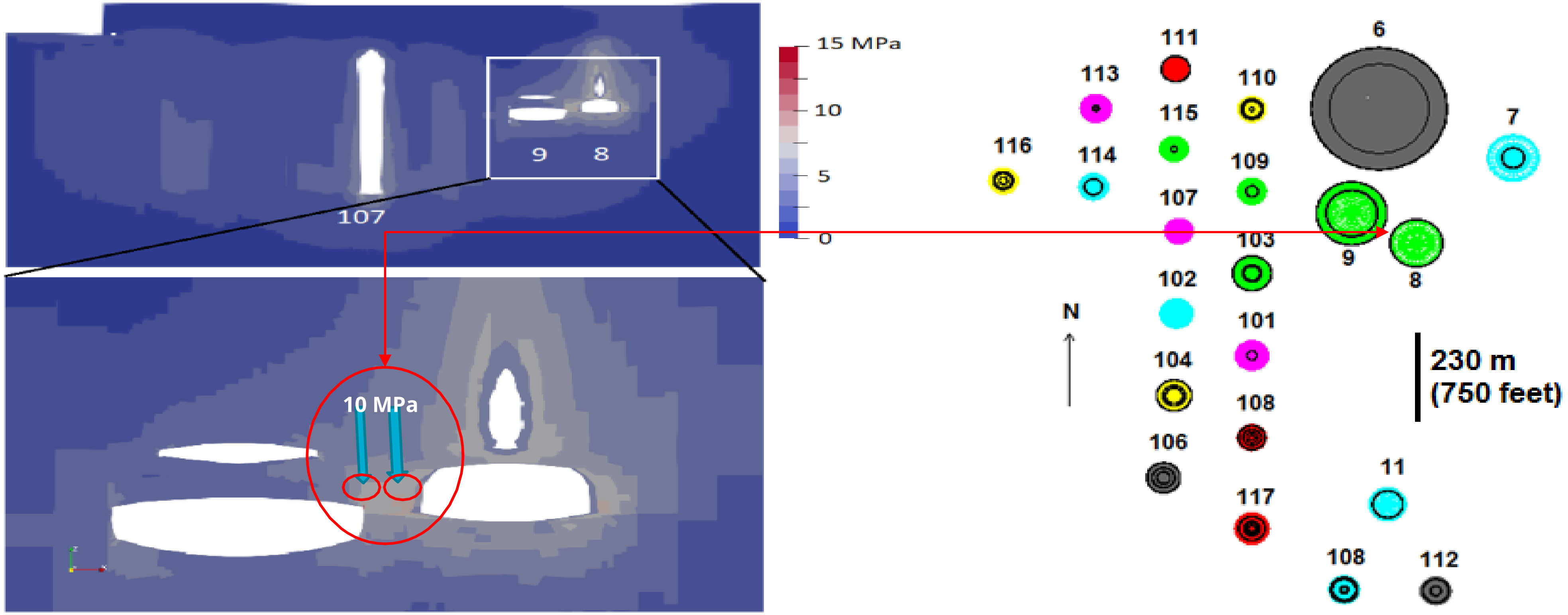
Low Equivalent Stress Creep - Why is it Important?





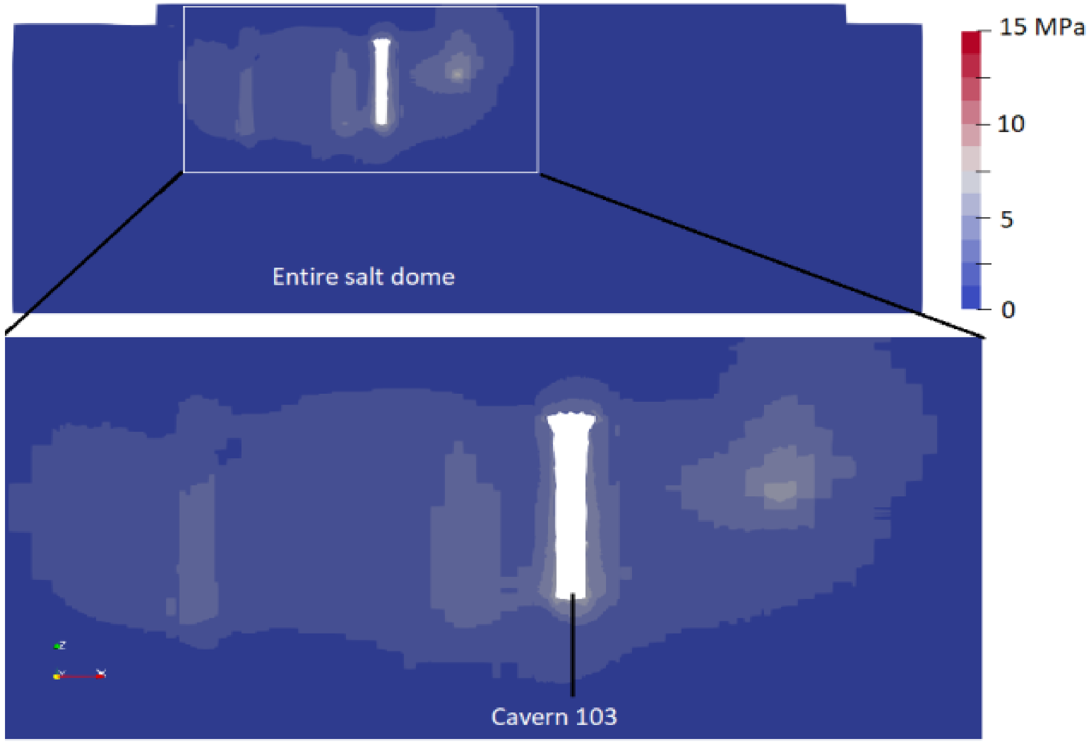
The volume of salt experiencing stress of 10 MPa or greater is significantly small compared to stress less than 10 MPa.

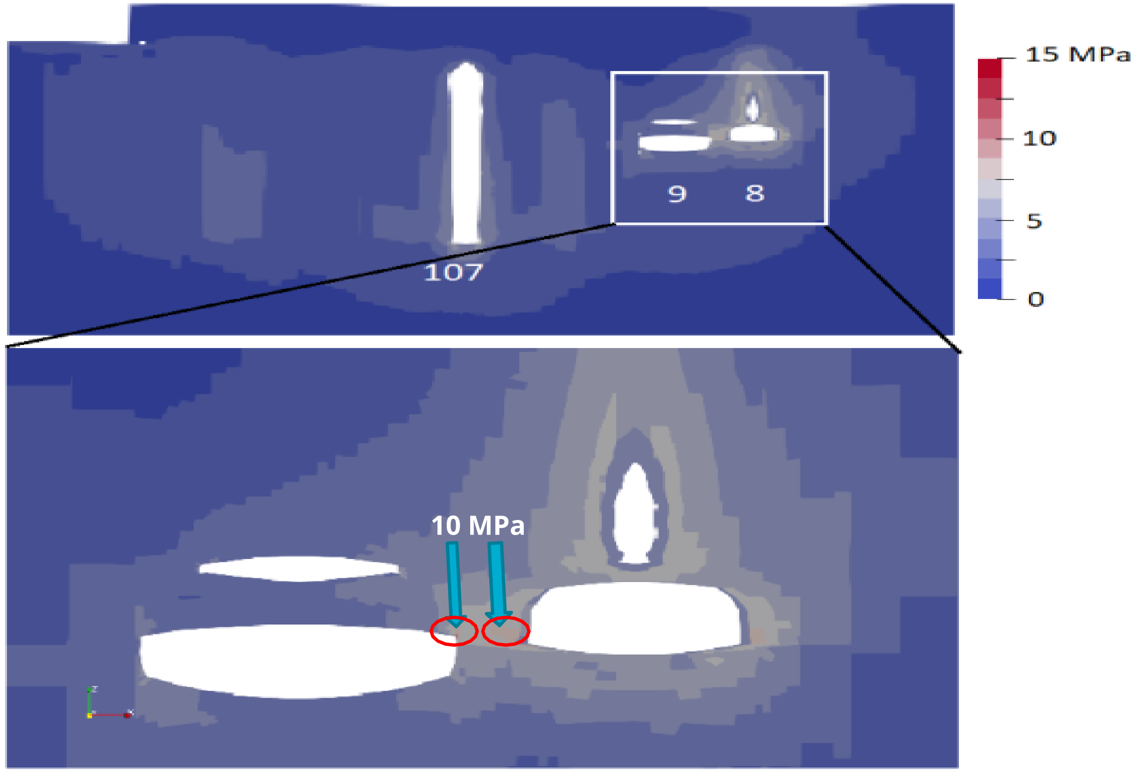
Low Equivalent Stress Creep - Why is it Important?



The volume of salt experiencing stress of 10 MPa or greater is significantly small compared to stress less than 10 MPa.

Low Equivalent Stress Creep - Why is it Important?





Our laboratory creep tests are sampling creep at equivalent stresses that comprise a very small percentage of the volume of affected salt in the dome.

What are we adding to the new M-D Viscoplastic Model?

Creep behavior at low equivalent stresses is probably pressure solution redeposition.

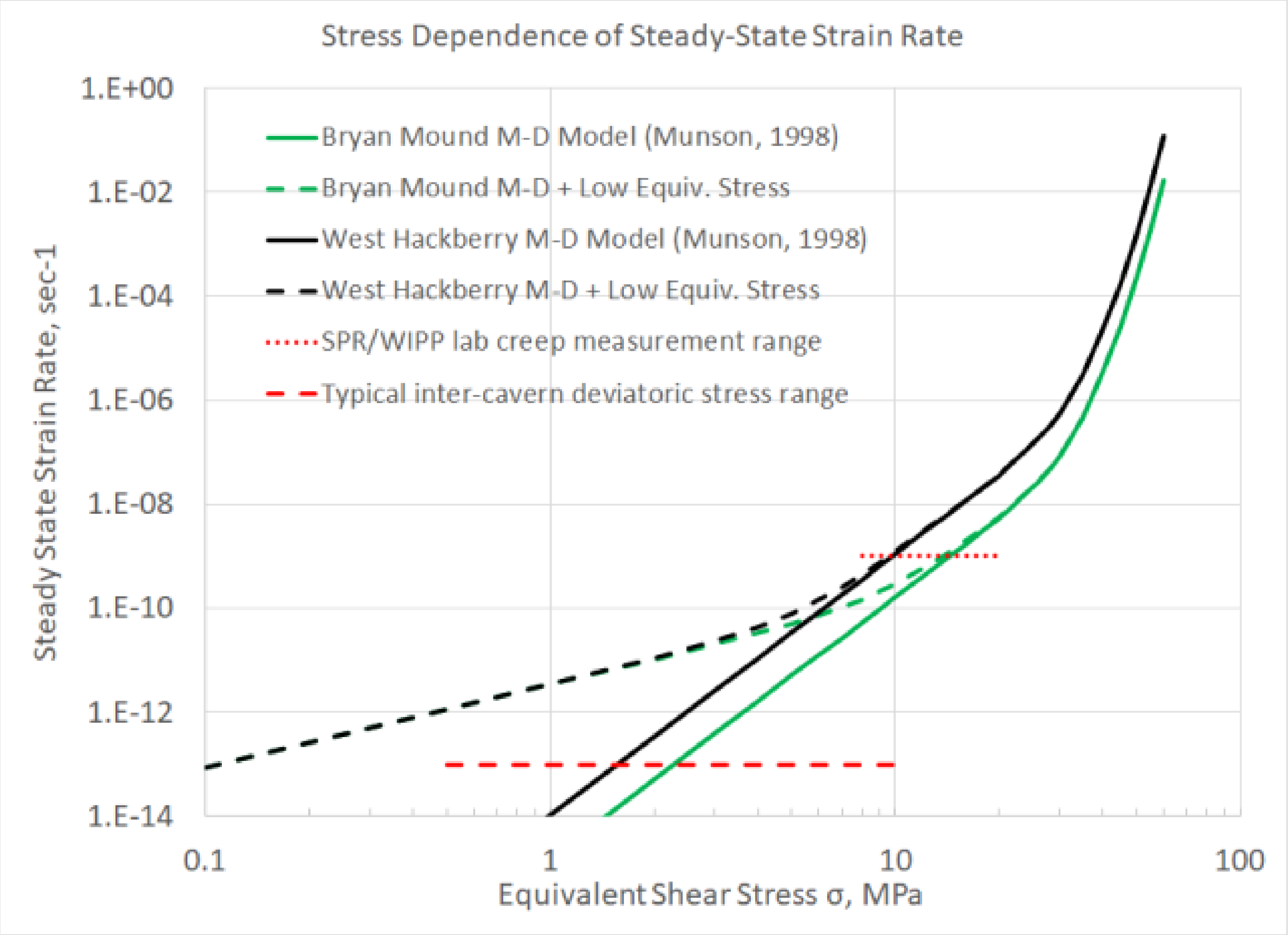
Reedlunn (2018) added a low equivalent stress mechanism (Mechanism 0) to M-D model (named M-D viscoplastic model); used combination of lab data, WIPP room closure to develop parameters.

Norton-Hoff formulation chosen for simplicity.

Note difference in strain rates for stresses less than 8 MPa.

West Hackberry model was rerun with addition of Mechanism 0, no other changes.

These runs were done to evaluate the new model. Lab data are required to quantify parameters.



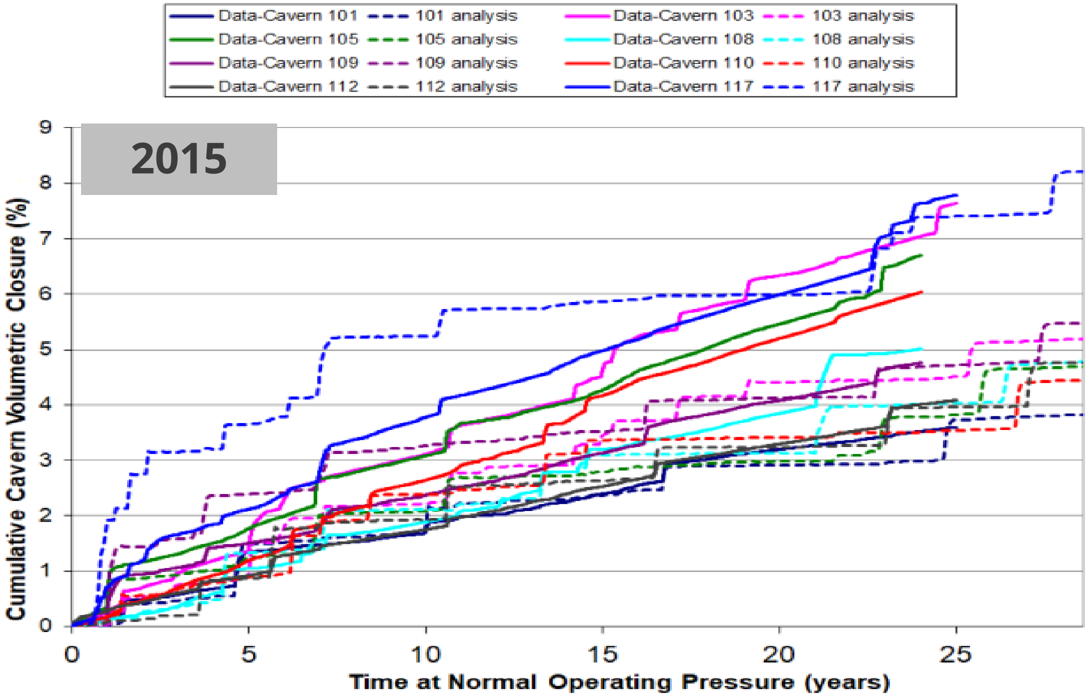
Extended M-D Viscoplastic Model Parameters for SPR

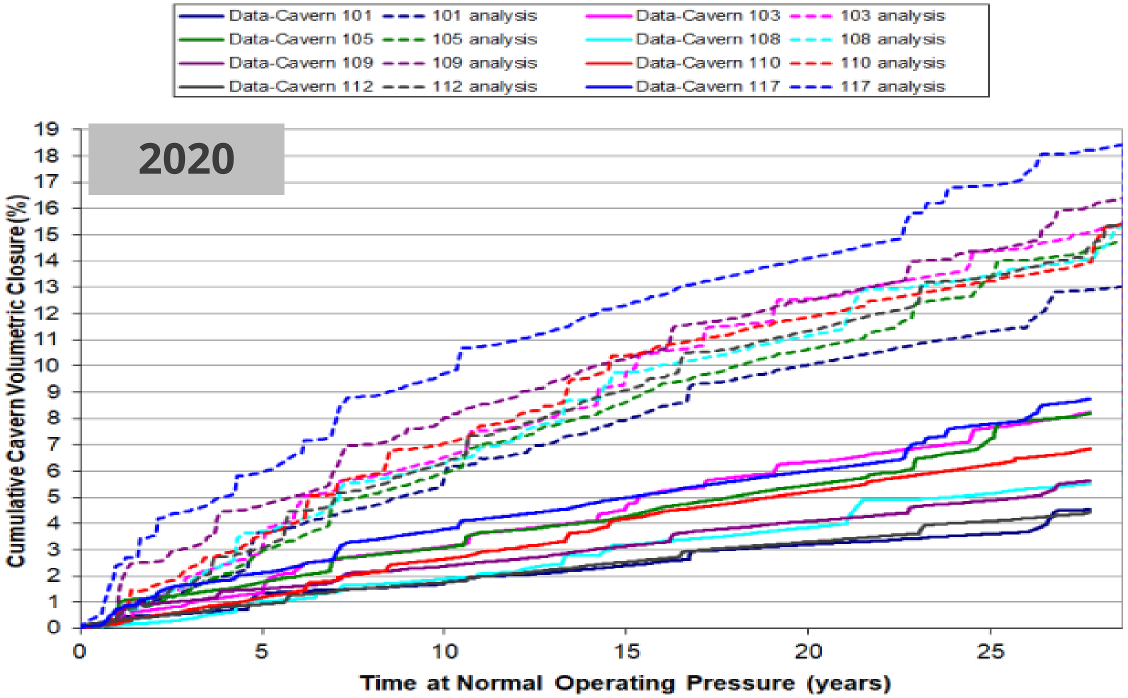
Property or parameter	Values
Primary Creep Constant $\mathbf{A_1}$, sec $^{-1}$	9.81×10^{22}
Exponent $\mathbf{n_1}$	5.5
$\mathbf{Q_1}$, cal/mol	25000
Secondary Creep Constant $\mathbf{A_2}$, sec $^{-1}$	1.13×10^{13}
Exponent $\mathbf{n_2}$	5.0
$\mathbf{Q_2}$, cal/mol	10000

$$\dot{\varepsilon}_i^{ss} = A_i \exp\left(-\frac{Q_i}{RT}\right)\left(\frac{\sigma_{eq}}{\mu}\right)^{n_i} \quad \text{for } i = 0, 1, \text{and } 2$$

Parameter	Values
Low Equivalent Stress Creep Constant $\mathbf{A_0}$, sec $^{-1}$	9.81×10^{22}
Exponent $\mathbf{n_0}$	5.5
$\mathbf{Q_0}$, cal/mol	25000

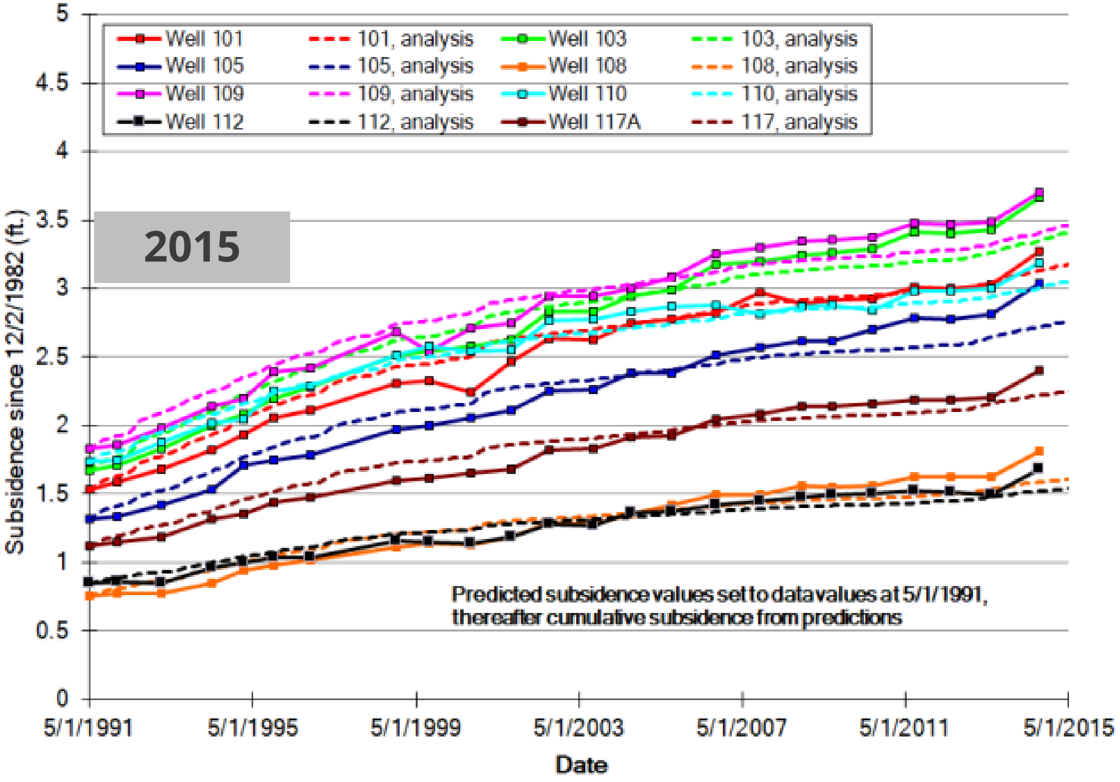
Cavern Volume Closure with Multiplier Comparison

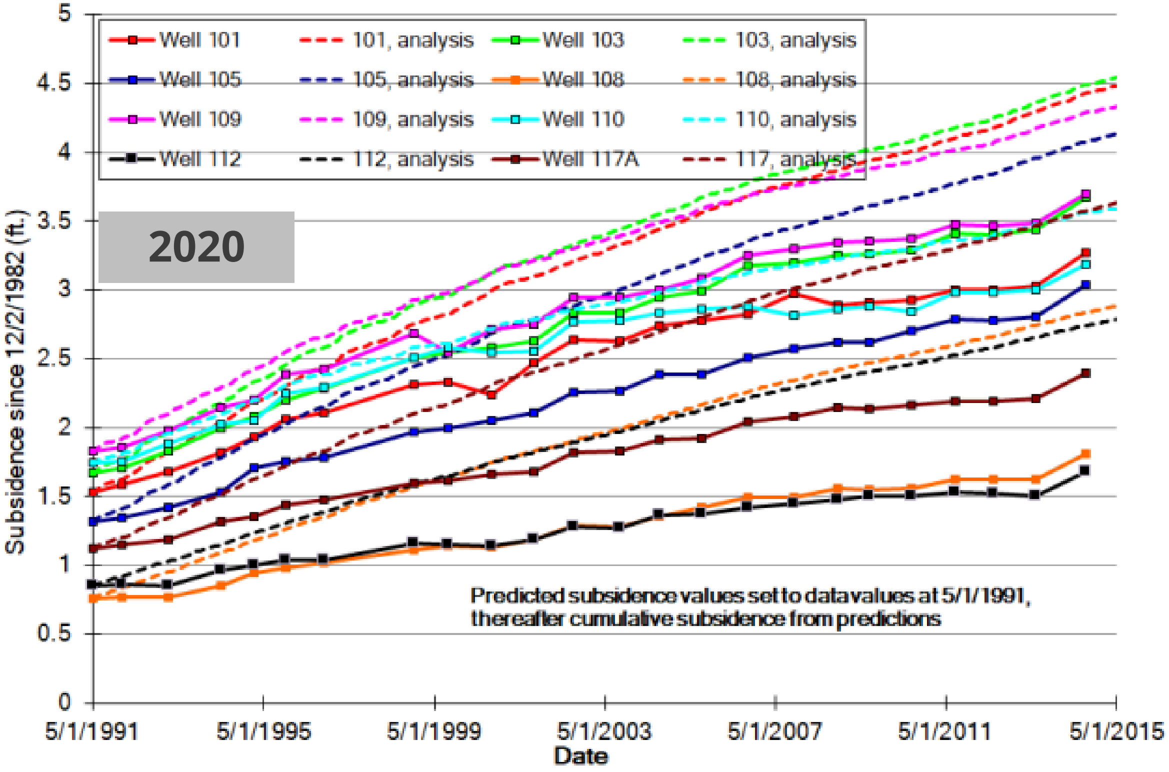




MD creep model with the use of Mechanism 0 had a significant effect on the cavern volume closure

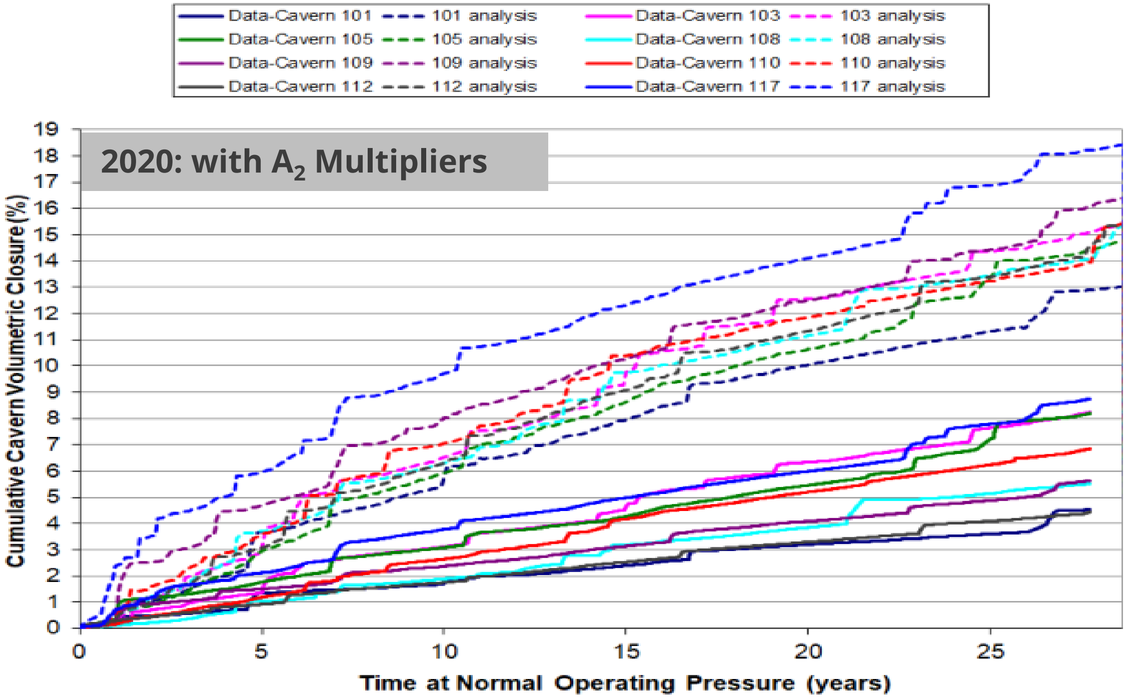
Surface Subsidence with Multiplier Comparison

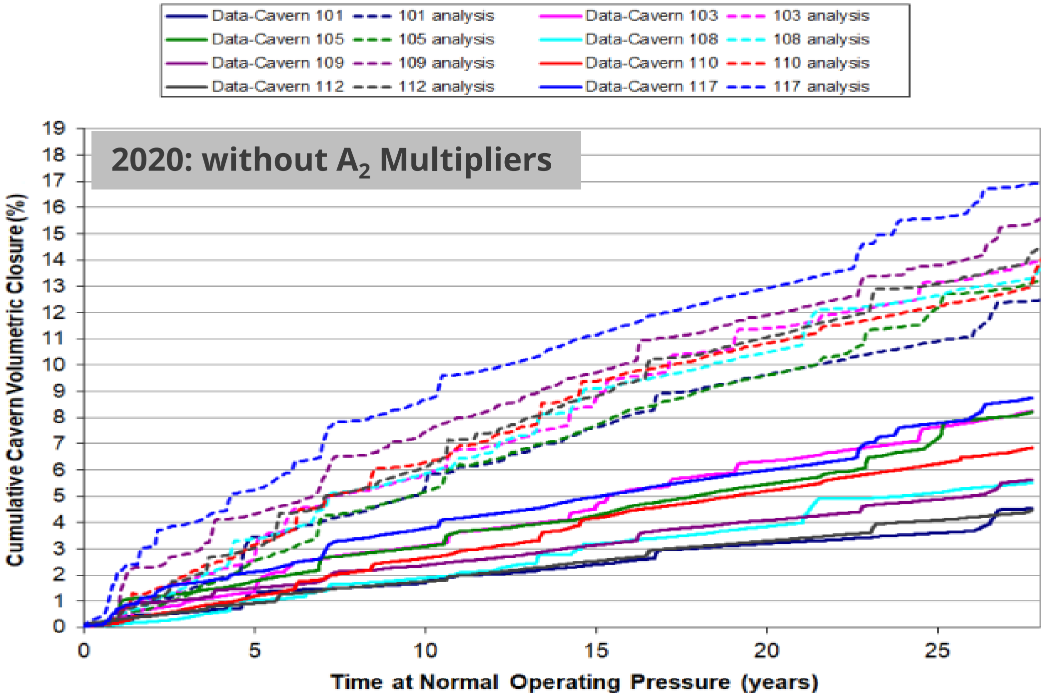




MD creep model with the effects of adding the low stress creep mechanism on the predicted surface subsidence. Surface subsidence predicted higher values compared to 2015.

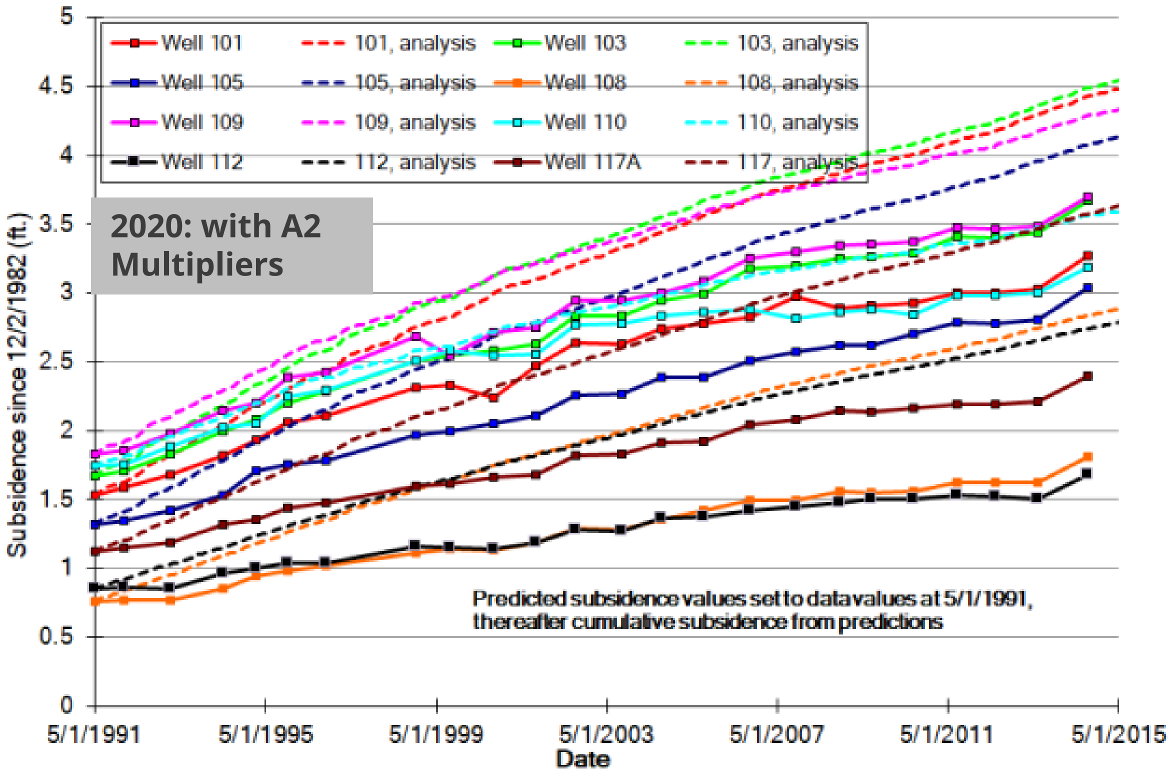
WH Model for Cavern Volume Closure no Multiplier

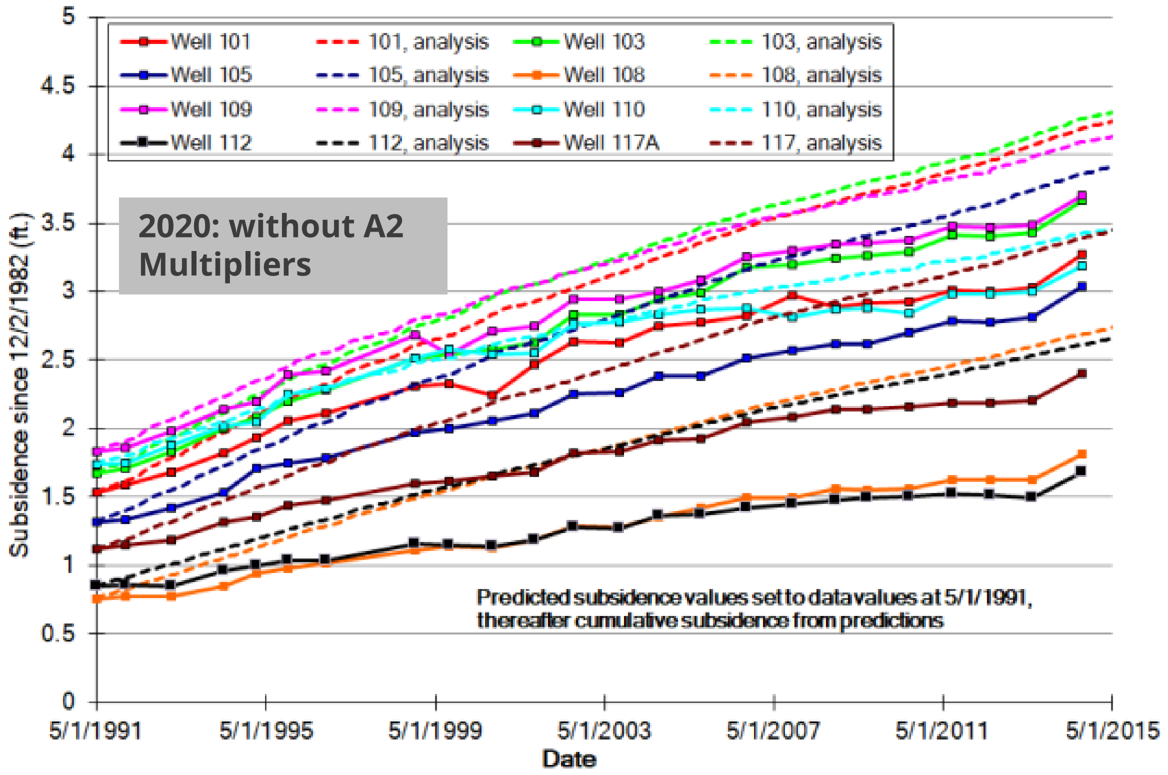




MD creep model with the elimination of the multiplication factors to the original M-D creep parameters, along with the Mechanism 0 creep parameters. Cavern volume closure volume decreased with the removal of the multiplier.

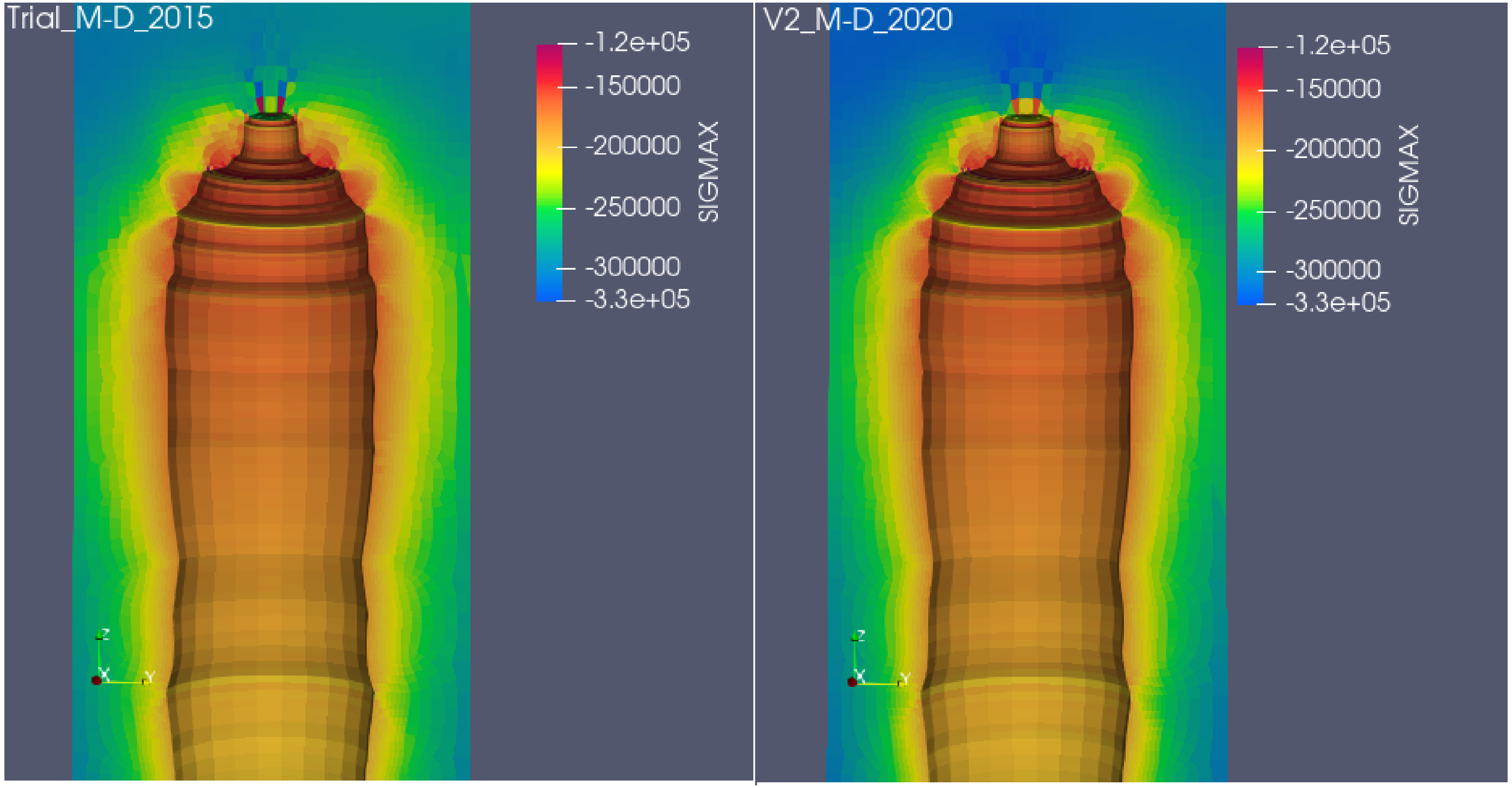
WH GM Model for Surface Subsidence no Multiplier





MD creep model with the elimination of the multiplication factors to the original M-D creep parameters, along with the Mechanism 0 creep parameters. Surface subsidence decreased with the removal of the multiplier.

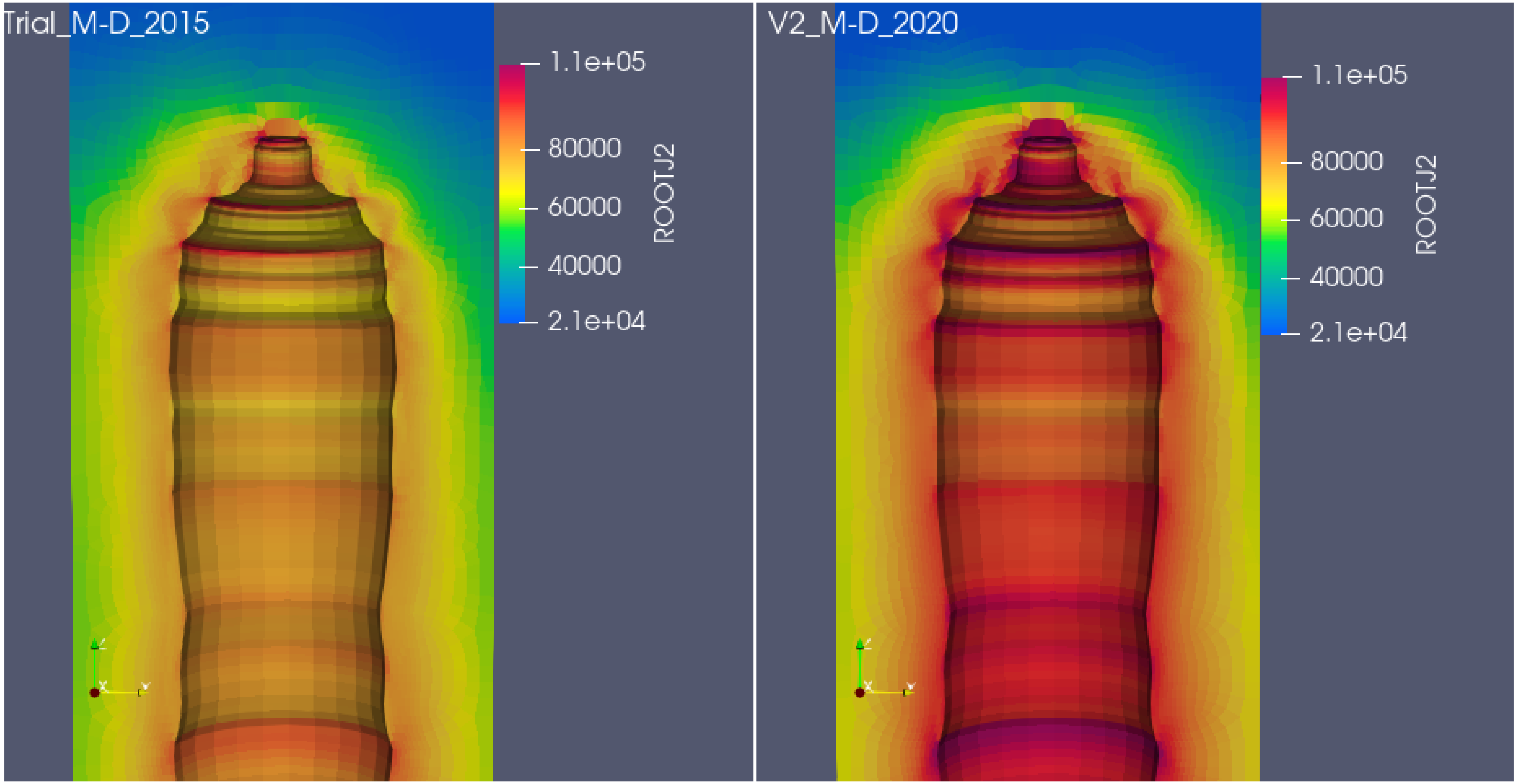
Effect on predicted normal stresses



Predicted maximum principal stress (tension positive; in pounds/square feet) around cavern WH-108 using the M-D model (left) and the M-D viscoplastic model (right).

Some slight difference in the distribution of stresses around the wall of the cavern, but the maximum value is essentially the same for both models

Effect on predicted shear stresses



Predicted square root of the second invariant J_2 of the deviatoric stress tensor (measure of a shear stress).

Maximum shear stress values predicted by the M-D viscoplastic model are approximately 30% higher than that predicted by the M-D model, with both occurring near the top of the cavern.

May be important in evaluating the potential for salt falls in the cavern.

Effect on predicted borehole casing strain

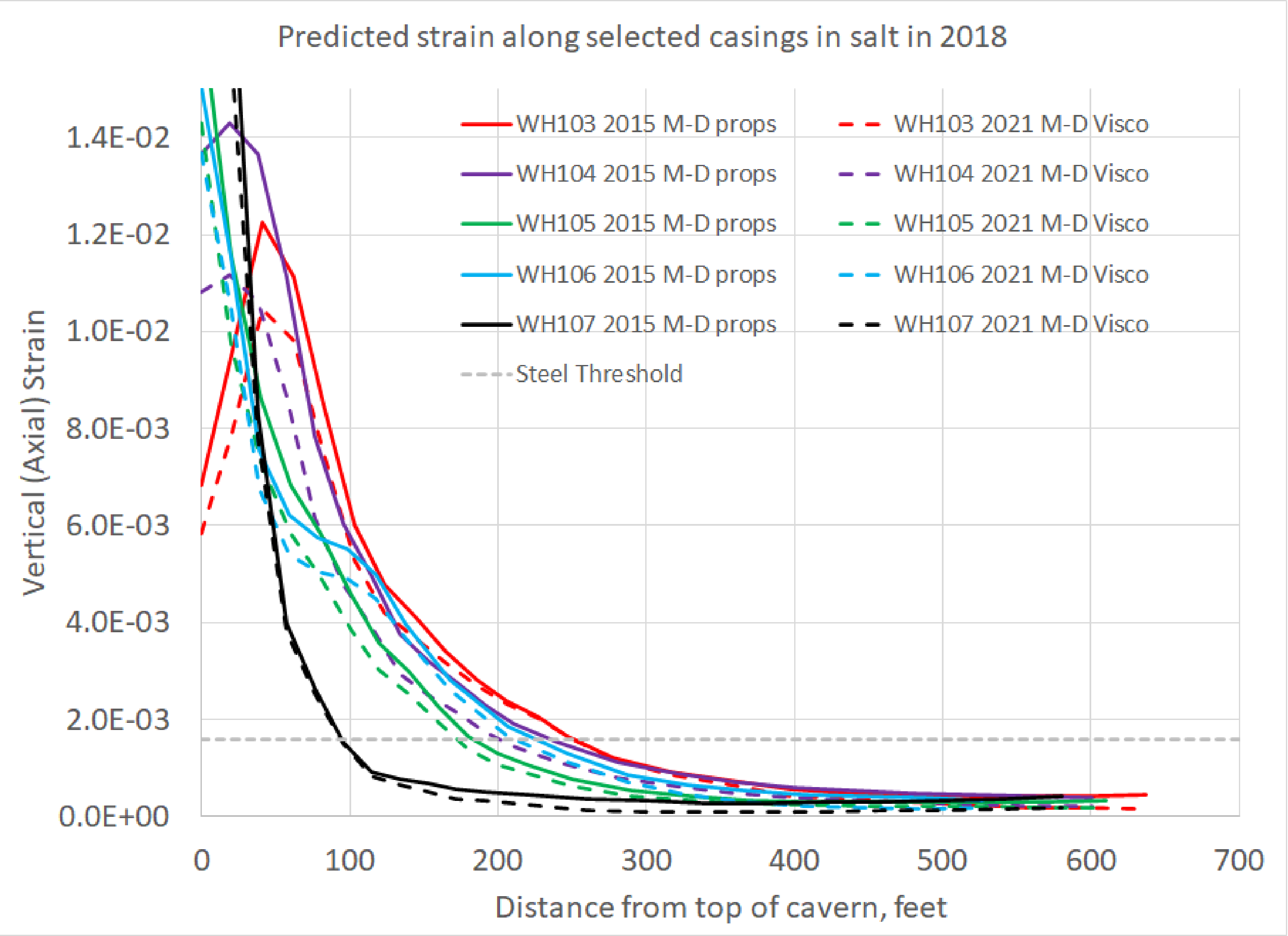
Predicted axial strain along wellbore casings.

The strains are predicted to be highest near the top of the cavern.

Cavern roof shape has effect on location of highest strains.

Predicted displacements and strains were found to be highly variable as a function of the property values used for the low stress creep mechanism.

** Important to get reliable laboratory data on which to establish appropriate property values, so that the effect on predicted cavern and casing behavior can be better quantified.



Conclusions

- Addition of low equivalent stress creep component (Mech. 0) accounts for deformation of large volume of inter-cavern salt, increases predicted steady-state cavern closure.
- Addition of low stress creep allows for use of laboratory-developed parameters for original M-D properties for higher-stress creep.
- Important to get enough reliable laboratory data on which to establish appropriate mathematical model for low equivalent stress creep behavior, so that the effect on predicted cavern and casing behavior can be better quantified.
- A better understanding of low stress creep mechanisms will have a significant impact on the evaluation of site operations on well and cavern integrity.

THANK YOU FOR YOUR ATTENTION