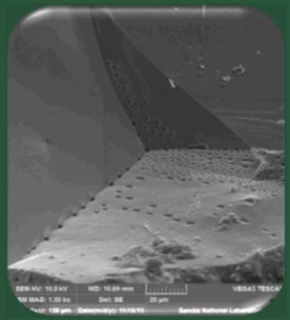
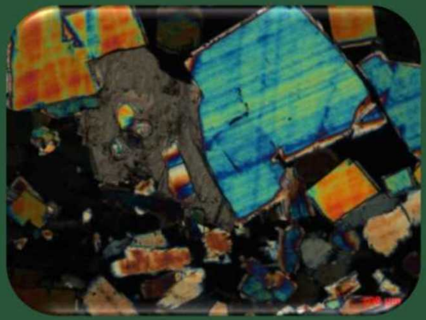
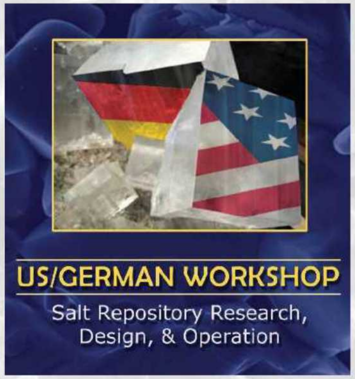




SAND2018-9349PE

Supplemental Discussion – Comparison of Bedded vs. Domal Salt

9th US/German Workshop on Salt Repository Research, Design, and Operation



PTKA Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
BGE TEC BGE TECHNOLOGY GmbH
BGR
Federal Ministry for Economic Affairs and Energy

- Steven R. Sobolik, Sandia National Laboratories, Albuquerque, New Mexico, USA

- Hannover, Germany
- September 10-11, 2018

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Introduction

- US-German Workshops have focused effort on developing thorough understanding of salt repository design, analysis, operation, and long-term prediction.
- Necessary component of these efforts is predictive modeling of the mechanical behavior of the repository during the operational period and long-term.
  - Validation (Benchmark comparison of WIPP Rooms B & D)
  - Salt mechanical models & properties such as creep, strength, and dilatancy envelopes are based on laboratory tests
- Inevitably discrepancies exist between model results and observed behavior.

Characteristics of Repository Modeling

- Prediction of future repository behavior for operational concerns and long-term performance
- License application – demonstrate repository behavior compliance to specific set of regulatory standards
- Prediction of room closure rates for disposal, worker safety, and seal performance
- Capability to predict salt response to short-term stress changes (other than post-mining transient creep) not currently required

Cavern Modeling

Requirements have evolved over time

- Models originally required to provide prediction of surface subsidence, rate of cavern closure for capacity planning; used single creep model, set of properties based on limited lab tests
- Early predictions were for long-term (20-50 years) future behavior; models eventually required validation with past behavior
- As storage sites age, new issues include highly variable cavern closure rates, cavern integrity, well casing integrity, accessibility to oil due to cavern geometry features (sagging roofs, salt fall damage to hanging strings)
- These issues require **confident** analysis of transient creep response of salt to short-term, large pressure changes

Progression of Complexity of Salt Cavern Geomechanical Models

Earliest Models	Progression of Model Complexity	Reason for Model Advancement
Primary Purpose: Long-term projection of surface subsidence, cavern volume closure	Primary Purpose: Analysis of individual cavern behavior, use as diagnostic tool, aid for developing strategies for well & cavern integrity management and remediation	As the sites age after 35+ years of use, creep-induced and other problems occur, requiring modeling tools with better resolution, validation, and problem-solving utility
Simplified dome geometries (30-degree wedge to simulate 19-cavern field; half-dome with symmetry axis)	Full dome included in model; initially as extruded "cylinder" of footprint, now as genuine rendering of shape based on seismic data	Need to know geomechanical behavior of specific caverns based on geometry, location, proximity to side of dome (post-Bayou Corne)
Caverns shaped as simple cylinders or frustums	Caverns shapes based on axisymmetric (and now, true) renderings of sonar-measured geometries	Need to know GM behavior resulting from cavern geometry – effect on dilatant/tensile stresses, casing integrity
Power law creep model (single steady-state mechanism)	M-D creep model (Multiple steady-state creep mechanisms with transient; Munson, 1998)	Need to evaluate cavern response to transient large ΔP events such as workovers

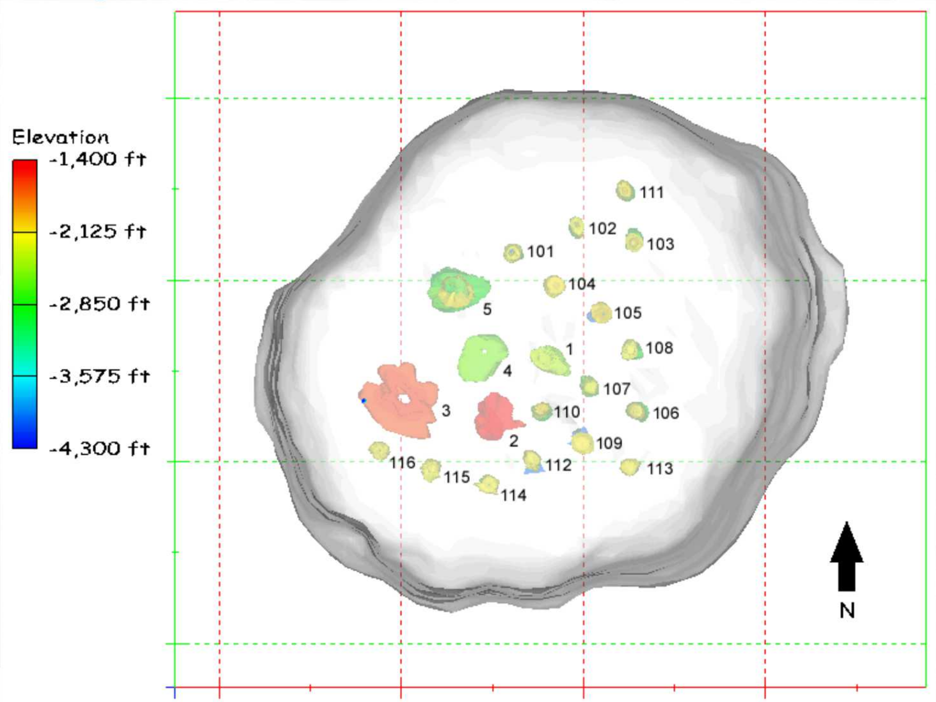
Progression of Complexity of Salt Cavern Geomechanical Models

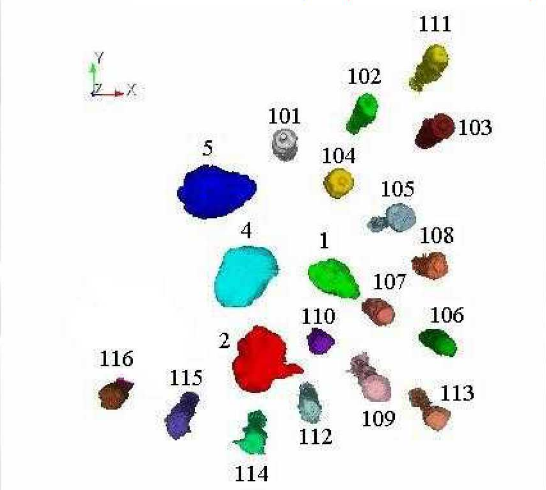
Earliest Models	Progression of Complexity	Reason for Advancement
Single set of salt creep properties based on lab tests of up to 6 samples (Munson, 1998)	Cavern-specific creep properties (K_0 transient multiplier, A_2 steady-state coeff.) calibrated to try to match measured cavern volume closures	Volume closure rates for caverns of similar geometry, depth vary across a site: West Hackberry by factor of 3, Bryan Mound by factor of 10
Model predictions compared to historical cavern volume closure, surface subsidence, one single A_2 multiplier for entire site (power law creep)	Same data used for model calibration, with partial success; for West Hackberry, K_0 from Munson multiplied by 18.2, A_2 by 0.89-3.2	Better match of individual cavern closure performance hopefully leads to more confident predictions of future cavern behavior
Prescribed constant wellhead pressure with workovers at 5-year intervals	Historical wellhead pressures through current times, then future prescribed pressures	More accurate past history; sympathetic pressure behavior of caverns adjacent to those under workover
Simplified renderings of salt dome, caprock, surrounding rock as single-unit, homogeneous (no faults or shear zones), perfectly bonded	Inclusion of regions with significantly different creep properties; inclusion of low E/low strength interface zones between salt & caprock, salt and surrounding rock	Site-specific observations: casing damage at salt-caprock interface at Big Hill; interface zone, inward-slope at salt dome wall for Bayou Choctaw; different salt zones at Bryan Mound

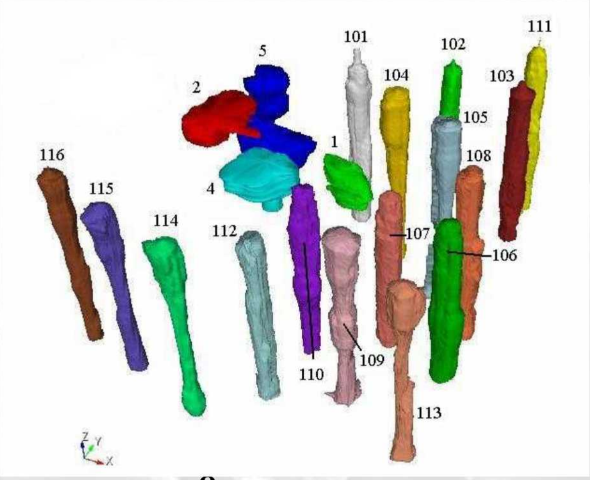
Two SPR model examples

- Bryan Mound – highly variable salt dome
  - Highly heterogeneous salt
  - Bizarre cavern shapes, caused by anhydrite/clay seams and impurities, faults, and shear zones
  - Gas intrusion from outside the formation into several caverns
  - Caprock steam-mined for sulfur in 1920s
  - Abandoned large-diameter cavern in middle of site, ongoing concern for potential cavern collapse
- West Hackberry – well-constrained salt dome (not included in these slides)
  - Homogeneous salt
  - Axisymmetric caverns
  - No obvious fault or shear zone features
  - Competent caprock

Bryan Mound SPR Site



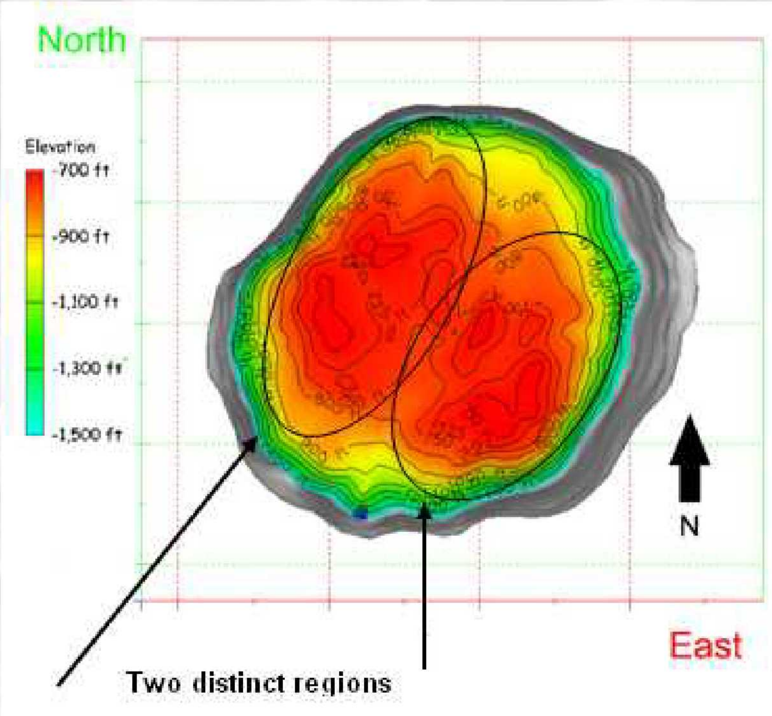


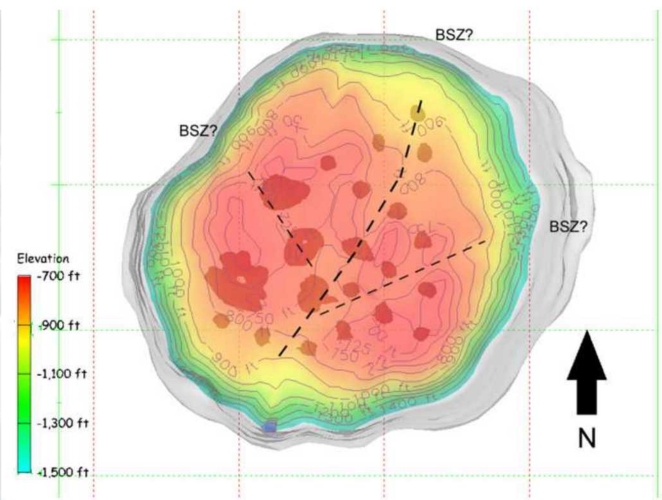


Bryan Mound site includes:

- ~226 MMB of oil storage.
- 4 unusually-shaped storage caverns (#1, 2, 4, 5) built in 1940s-1950s.
- 16 cylindrical-shaped storage caverns (#101-116) built in early 1980s.
- Approximately 230 m sandstone overburden, 85 m anhydrite/ carbonate caprock over salt dome.
- **Highly heterogeneous salt** with anhydrite/clay seams, faults, shear zones
- Caprock mined for sulfur in 1920s – large vugs, thermal signature remain

Heterogeneity of Salt



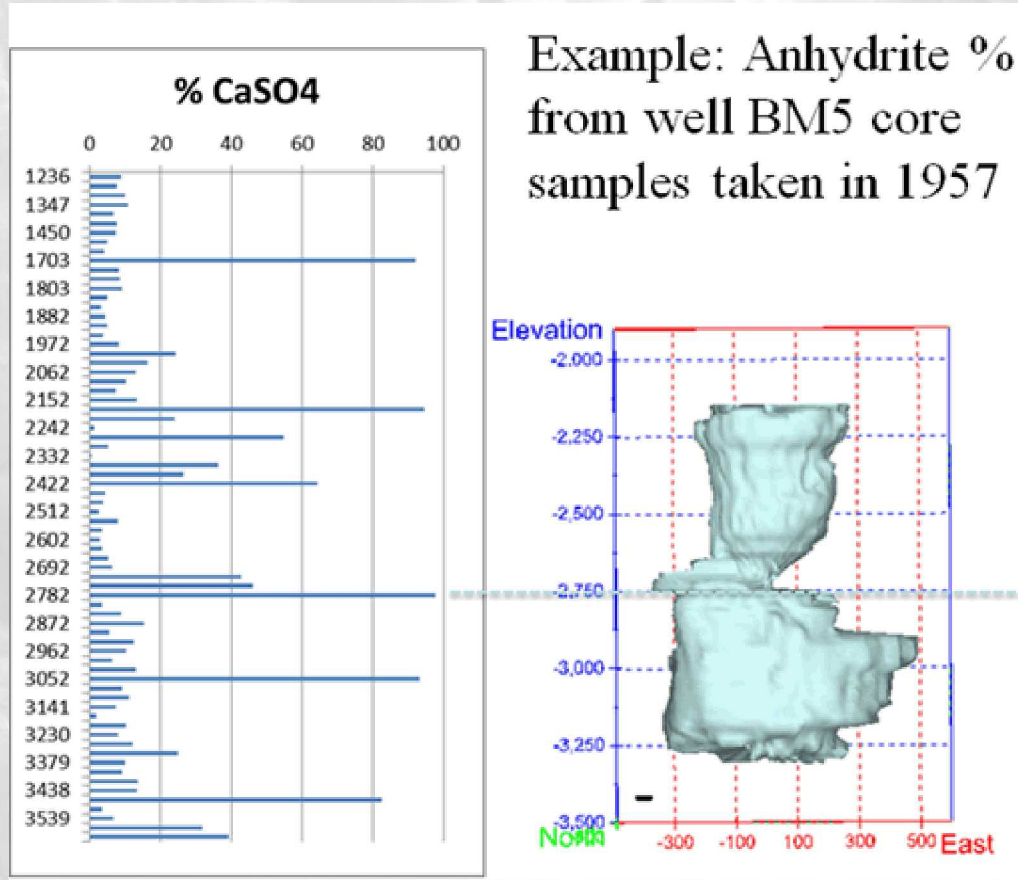


- Salt dome is bisected by several boundary shear zones consisting of faults, salt spines, anhydrite/clay seams, and other anomalies (from seismic, sonar, borehole data).
- Due to these features, the salt creep rates are highly heterogeneous across the site.

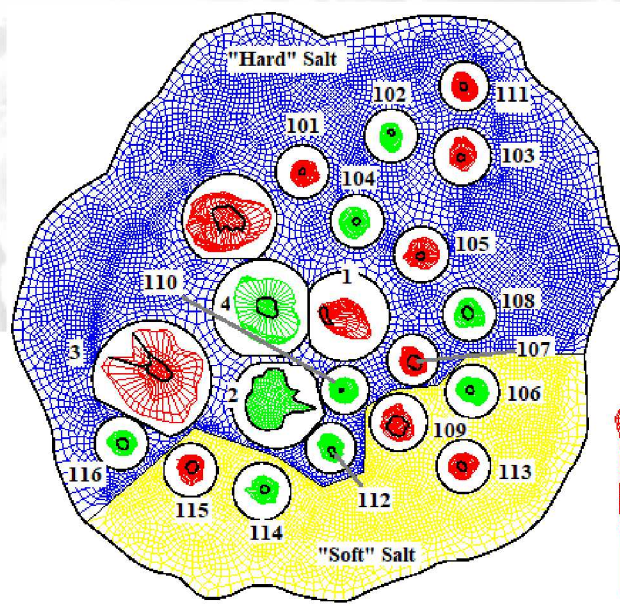
Cavern	Closure, BBL/yr	Cavern	Closure, BBL/yr
BM101	5,365	BM109	8,543
BM102	4,944	BM110	3,150
BM103	11,680	BM111	7,813
BM104	2,948	BM112	6,858
BM105	3,683	BM113	10,223
BM106	10,460	BM114	21,304
BM107	4,061	BM115	21,034
BM108	2,702	BM116	6,135

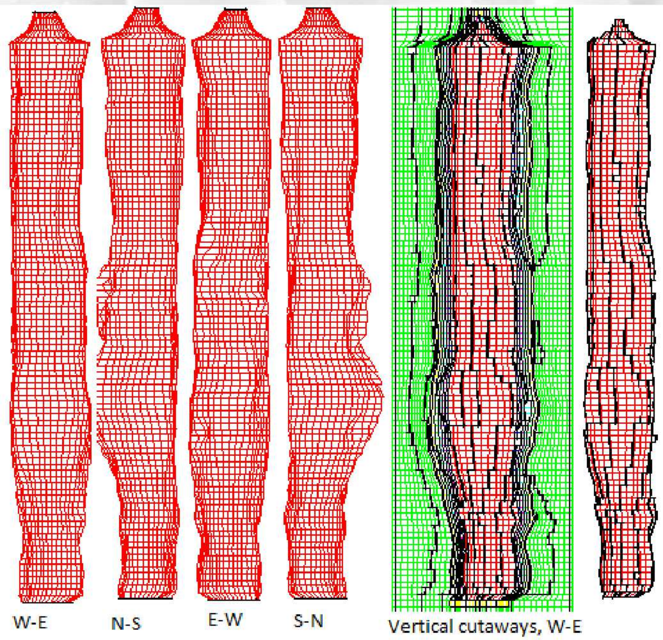
Bryan Mound Cavern 5

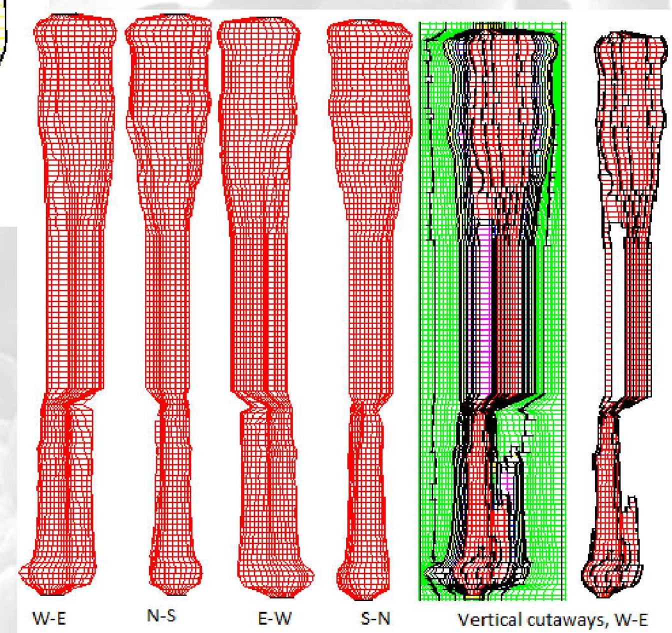
- 36 MMB volume (largest SPR cavern)
- Accessibility to oil in lower lobe
- Salt falls from neck region damaging string
- Emulsion issues when water is pumped in for oil removal
- Gas intrusion issues (anhydrite providing possible flow path)
- Casing failures due to large roof diameter
- Effect on stability of nearby caverns
- Difficulty in modeling creep due to heterogeneous impurity content



Full Dome Model for Bryan Mound

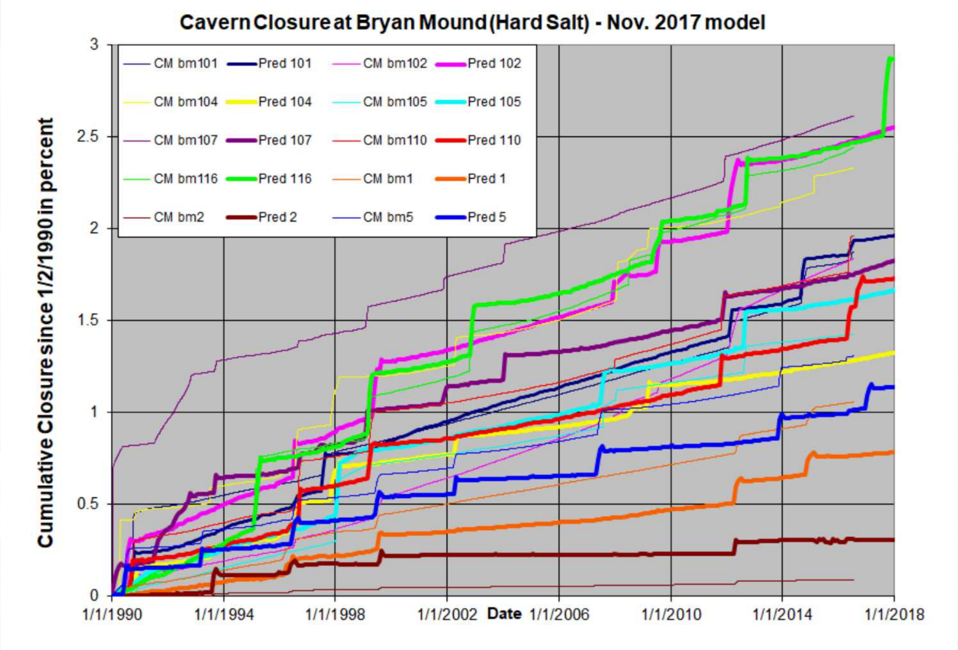


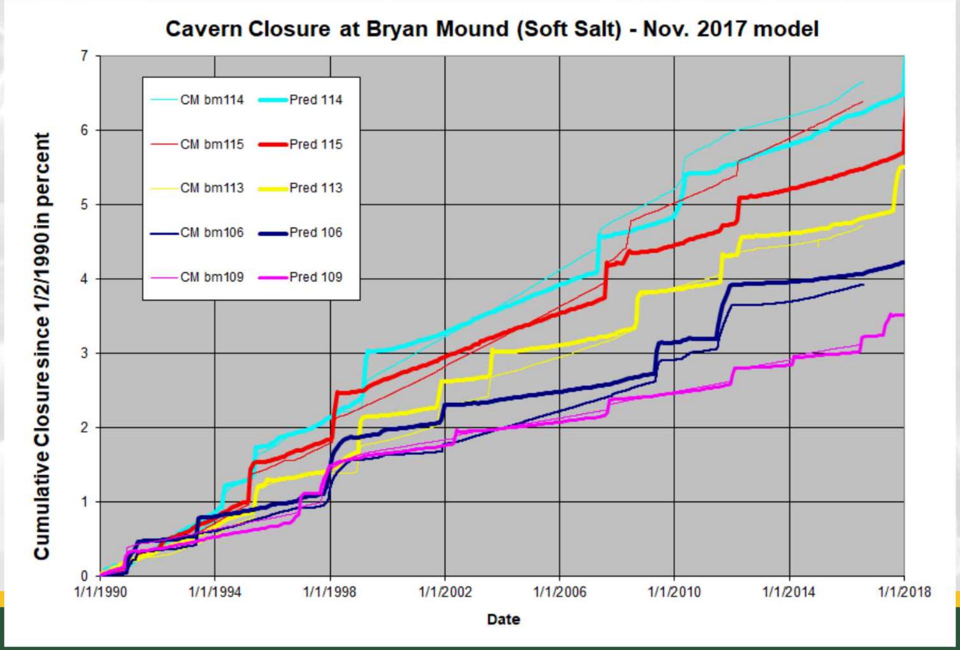




- All caverns meshes mapped to sonar-based geometries (BM-103, 105 shown)
- 5 leach layers ("onion skins") included for nearly all BM caverns

Bryan Mound – Cavern Closure





Salt of Cavern	A_2 multiplier	K_0 multiplier
Hard salt	2.3	1.0
Soft salt	24.0	1.0
BM-1	6.0	1.0
BM-2	19.08	1.0
BM-3	19.08	1.0
BM-4	31.0	1.0
BM-5	1.94	1.0
BM-101	1.89	0.1
BM-102	5.0	0.1
BM-103	50.0	0.5
BM-104	1.46	2.0
BM-105	1.85	1.0
BM-106	25.	1.0
BM-107	1.5	1.0
BM-108	0.14	1.5
BM-109	7.0	1.0
BM-110	1.5	1.0
BM-111	20.0	0.16
BM-112	1.5	1.5
BM-113	40.0	1.0
BM-114	200.0	1.0
BM-115	200.0	1.0
BM-116	4.36	1.0

- **2018 predictions using cavern-specific creep properties**
- **Cavern closures range from 0.1% to 1.0% over 20 years**
- **Improved (somewhat) correlation ; however, overpredict surface subsidence by factor of 1.5-2**

Summary

- Geomechanical modeling is not exact, often not close.
- Pre-repository prediction of behavior will ultimately not match measured behavior due to the application of homogeneous properties to a heterogeneous domain.
- Requirements of a site model will change/evolve during the lifetime of the site (pre-construction, early operations, later operations), and models will need to evolve accordingly.
- Laboratory tests will present a limited picture of the properties of salt in a repository domain.
- Knowledge of the nonconformities of a bedded or domal salt (faults, interfaces, clay or anhydrite seams, etc.) will introduce issues that may need to be addressed in upgraded mechanical models.