Analyzing the Effect of Large Pressure Changes on the Operational Stability of Large-Diameter Caverns for the Strategic Petroleum Reserve

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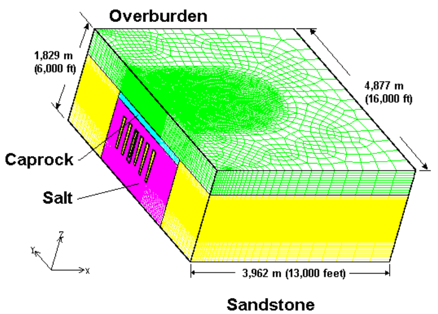

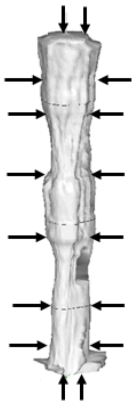

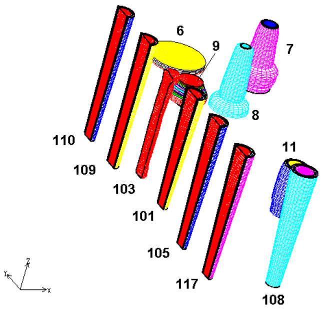

West Hackberry caverns, including five leachings (except for cavern 103)

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NNSA National Nuclear Security Administration

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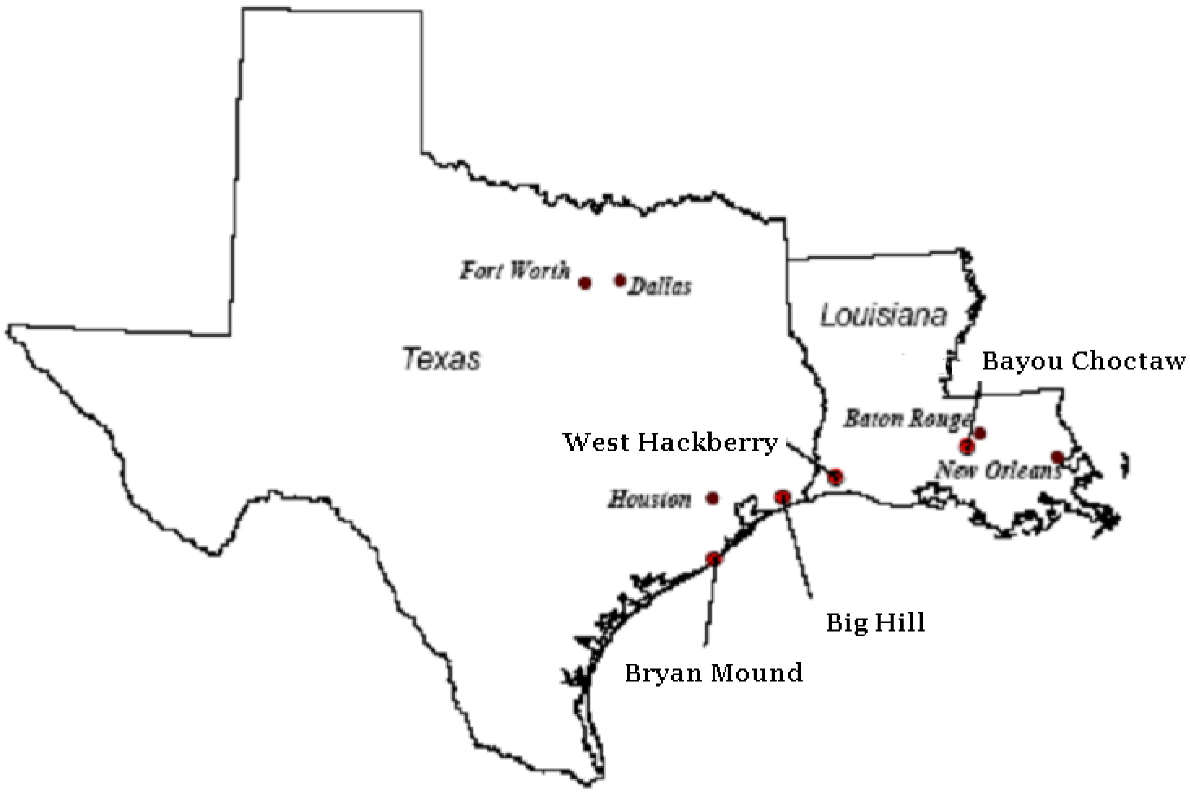
Today’s Presentation

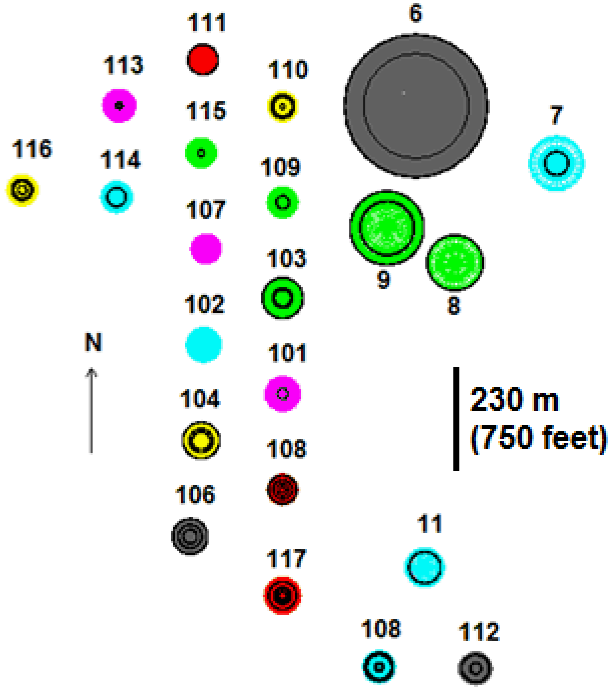
- Brief description of the caverns at the Strategic Petroleum Reserve’s West Hackberry site
- Description of the events at West Hackberry Cavern 6, a large-diameter oil storage cavern
- Description of 3-D geomechanical analyses of West Hackberry caverns and the Cavern 6 events and workovers
- Results of the analyses and recommendations for completion of workover operations
- Resulting effects on site operations

West Hackberry SPR Site



- West Hackberry site includes:
- ~228 MMB of oil storage in 22 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

Cavern Layout



- High creep rates put tension on casings
- Cavern 6 shape (~350 m diameter) causes significant ceiling subsidence, creating excessive potential for casing failures, loss of access to oil
- Proximity of Caverns 6/9/8 (~70 m between edge of Cavern 6, top lobe of Cavern 9) increases sympathetic pressure response, presents other operational issues regarding casing, cavern damage

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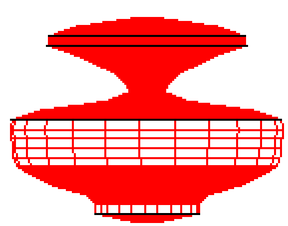

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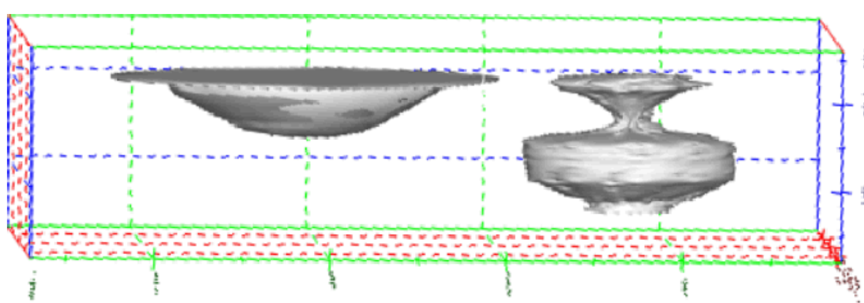
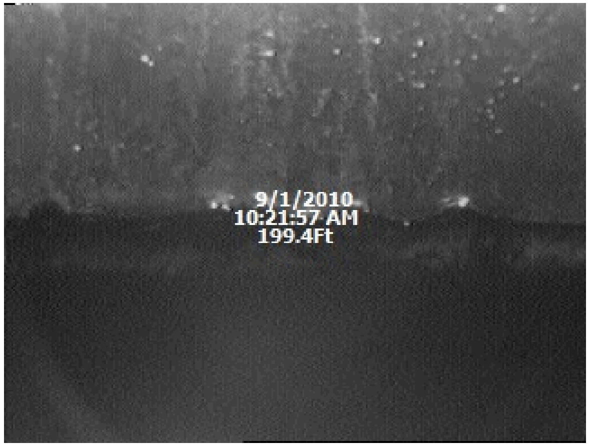


Events at Cavern 6



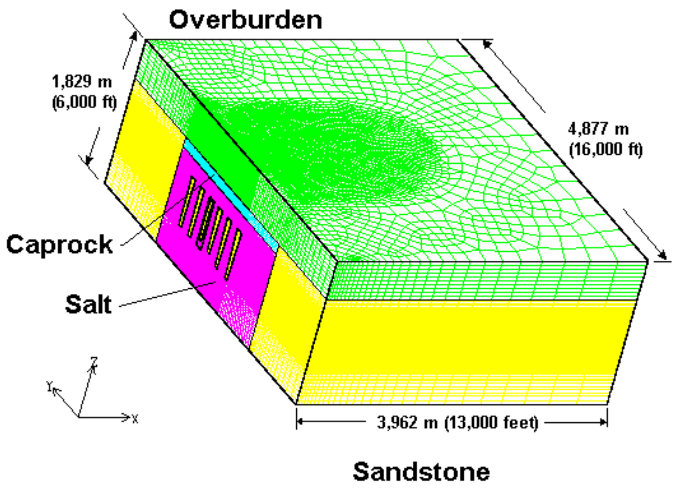
- Prior to 2010, Cavern 6 had 3 cemented, cased wells:
  - Well 6 (original) had 178-mm liner installed in 1977
  - Well 6B (added in 1978) experienced leak at 686 m (2250 feet) depth in 2001, had liner installed in 2002
  - Well 6C (added in 1978) experienced leak at 730 m (2400 feet) depth in 1988, had liner installed in 1990
- September 2010: Casing damage found at two locations in Well 6; workover (zero wellhead pressure) was commenced, decision was made to plug & abandon well, completed January 5, 2011
- May 2012: Cavern pressure data indicated leak in Cavern 6; workover commenced, resulting increased pressurization rate in Cavern 9 raised concerns of crack formation; also, workover increased strain rate on Well 6B.

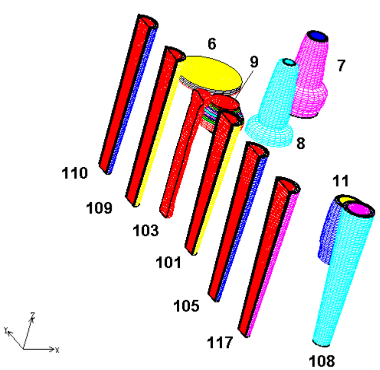
Request for 3-D Analyses

- September 2010 concerns:
  - Tensile cracking around Cavern 6 perimeter upon cavern repressurization after workover
  - Dilatant damage to salt around middle of Cavern 9
- Analysis: Model normal, alternate repressurization scenarios to develop process that avoids these concerns.

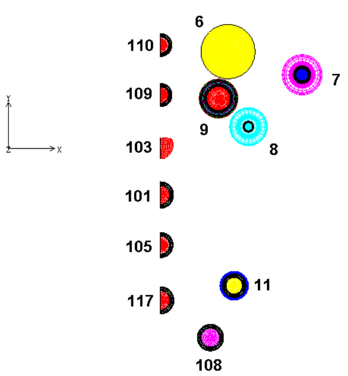
- May 2012 concerns:
  - Two workovers on Cavern 6 in two years putting excessive tensile strains on one remaining good well, 6B
  - Nearly 30 years of ceiling subsidence may have already made up to 0.20×10^6 m^3 (1.3×10^6 barrels) in the cavern rim inaccessible by normal fluid replacement techniques
  - Lost of Well 6B would make all 0.95×10^6 m^3 (6×10^6 barrels) inaccessible until new cavern entry is created
- Analysis: Calculate accumulated strain on Well 6B casings during 2012 workover, make recommendations for further mitigation actions

Description of 2010 WH Model





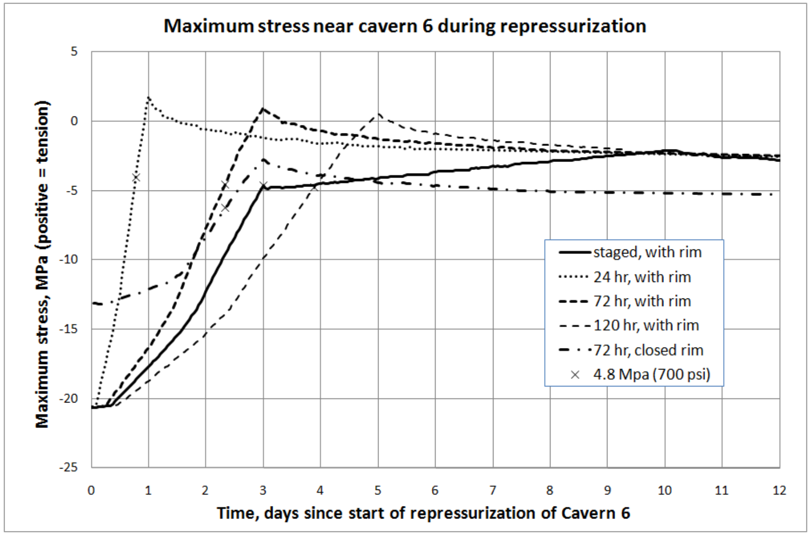
West Hackberry caverns, including five leachings (except for cavern 103)

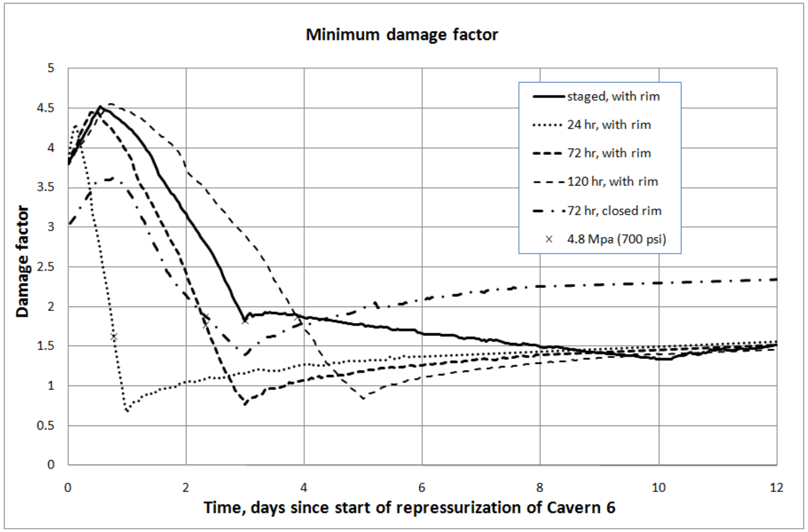


West Hackberry caverns, including five leachings (except for cavern 103)

- Eastern half of West Hackberry dome modeled; N-S symmetry plane through center caverns
- Computational mesh includes 1.29×10^6 elements, 4 material types
- Sandia-developed finite element code JAS3D, run in parallel mode on 32 processors
- Multi-mechanism deformation (M-D) model used for salt creep modeling; includes transient and steady-state creep components; salt properties from Munson (1998), fit to match site data (cavern closure, surface subsidence)
- Pressures in caverns are explicitly input into calculations
- Five-year workover schedule included in model; explicit workovers for Cavern 6 used for these analyses

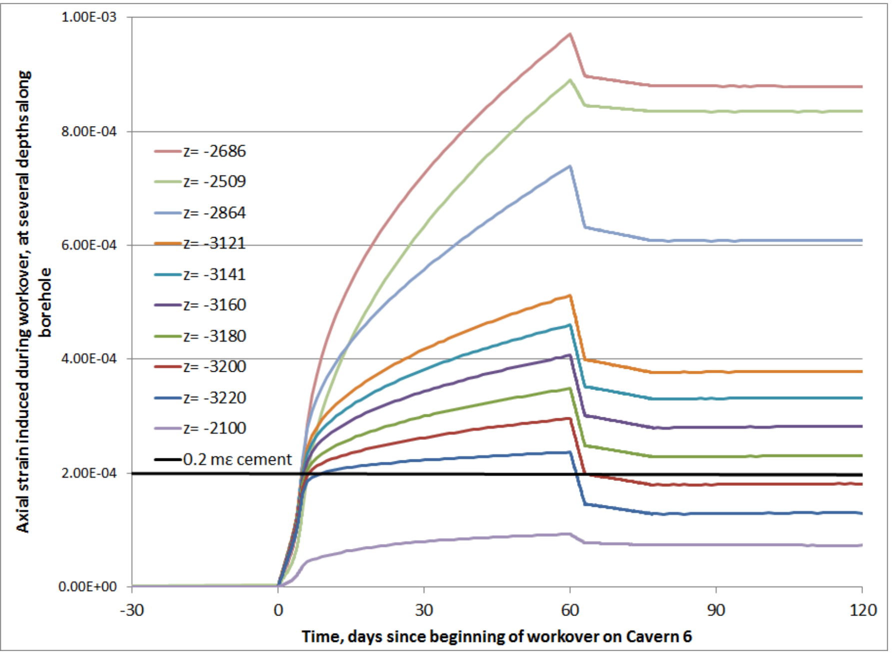
Results of 2010 analysis





- 5 different repressurization scenarios were modeled, based on rate of repressurization to normal wellhead pressure
- Recommendation for staged repress-urization (raise wellhead pressure from 0 to 4.8 MPa (700 psi) in 3 days, followed by 7-day period raising the pressure to 5.9 MPa (850 psi); based on maximum stress, dilatant damage factor around perimeter of Cavern 6
- Analysis also showed long time (over 15 months) to return salt stresses to pre-workover conditions, recommendation to require at least one year between workovers of Caverns 6 and 9

Results of 2012 analysis



- Axial strains in the salt around well bore are significant every time a workover on Cavern 6 is performed, exerting as much as additional 0.9 mε during a 60-day procedure (cement threshold strain 0.2 mε, steel casing 1.6 mε).
- Highest strains predicted to occur at 2500-2700 feet depth.
- Strains continue to grow as the cavern is held at low pressure.
- Because Well 6B has undergone two workovers in the past three years, it is at a high risk of exceeding plastic strain threshold and failure

Results, Recommendations

- Resulting effects on site operations
  - Based on SNL recommendations, Cavern 6 oil being removed (probably permanently) for better ability to assess condition of ceiling and perimeter, volume of trapped oil
  - Plan being developed for long-term maintenance of Cavern 6 to prevent adverse impact to nearby Caverns 8, 9
  - Because of concerns of sympathetic pressure response, currently conducting analyses to determine workover time limits for Caverns 8, 9
  - GPS/tiltmeter installation above WH-6 for detection of subsurface activity; seismic monitoring also likely to be installed
  - Seismic mapping of Cavern 6 being investigated to better determine shape of cavern ceiling, accessibility of oil

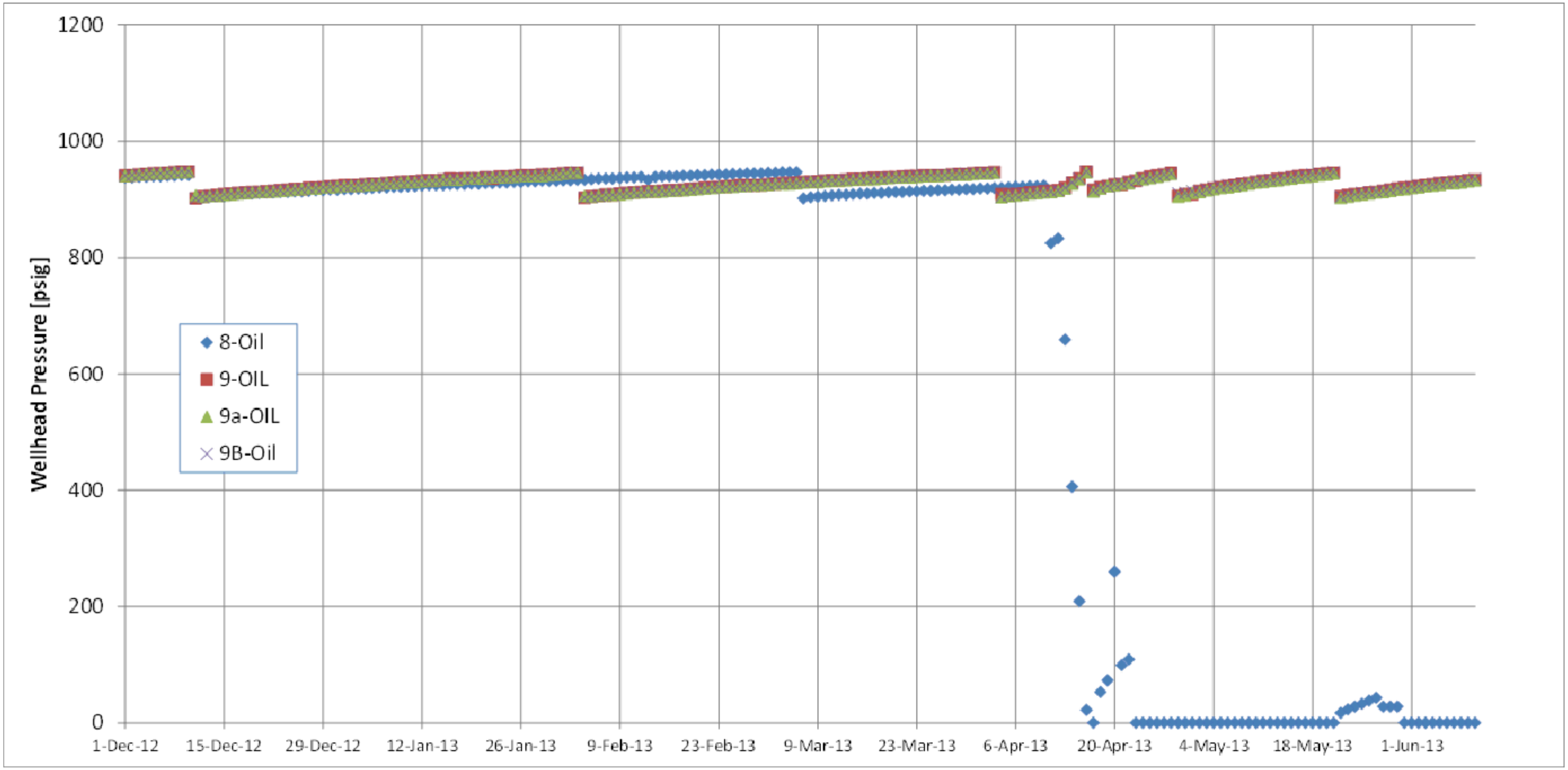
Evolution of WH model, analyses

- For current Cavern 8/9 analyses, model has been updated:
  - Enlarged mesh includes full dome, all 22 caverns, all cavern geometries based on sonar-measured geometries, contains nearly 6 million elements
  - Transitioning calculations from JAS3D to Adagio, part of Sandia-developed Sierra analysis suite (Arguello, 2013, 47th US Rock Mechanics Conference)
  - Developing post-processing capability to convert predicted cavern volume closure to expected pressure increase, to compare with site pressure data and eventually use as diagnostic for understanding sympathetic pressurization rate increases

Thank you!

Extra Slides

Example of Sympathetic Pressurization



- Normal pressurization rate due to creep-induced cavern closure increases when nearby cavern undergoes workover; drop in pressure in one cavern changes principal stress differential in vicinity, inducing higher transient creep

What is a geomechanical model?

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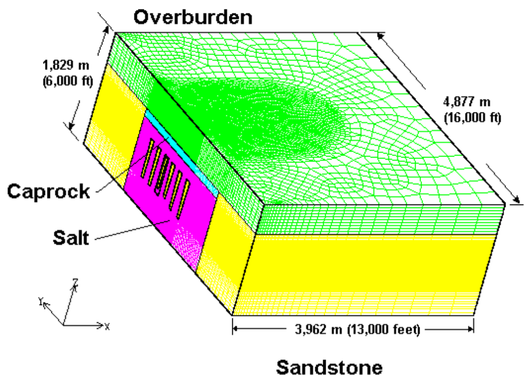
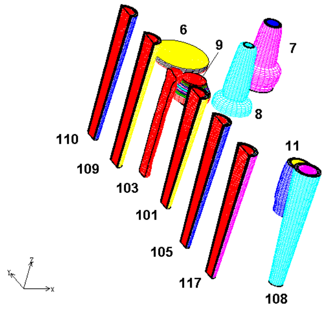
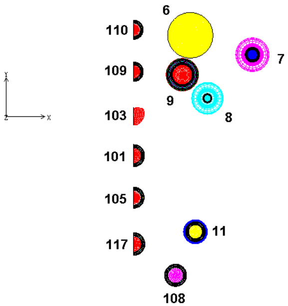
- A geomechanical model calculates the stresses and strains at millions of points within a geological region. The modeler uses these calculations to predict cavern closure, surface subsidence, and stresses and strains on wellbore casings. It does this using the following:
  - A three-dimensional mesh representation of the rock types and features of an area, including the salt dome and caverns
  - Standard engineering mathematical equations for stresses and strains, including the mathematical models for different types of rock behavior
  - Salt creep property values determined from laboratory tests on salt core samples, and modified using site data to match predictions
  - Workover schedules
  - Geothermal gradient





West Hackberry caverns, including five leachings (except for cavern 103)



West Hackberry caverns, including five leachings (except for cavern 103)

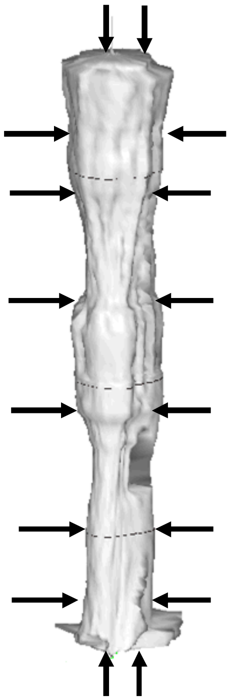
Limits of Geomechanical models

- Simplified geometries in the mesh (although these are continually getting more realistic)
- Models reflect current understanding of site behavior, and can be improved with new info (i.e., BH salt/caprock slip)
- Pressure in caverns is explicitly input into calculations; i.e., calculations cannot be used to predict pressure change due to cavern closure, or pressure change in one cavern when adjacent cavern is in workover
- No flow modeling (oil/brine movement, gas intrusion, salt dissolution, etc.)
- Must explicitly (if desired) include features such as faults (which has been done for Big Hill) and casings (which is currently being developed for BH)

What is creep?

- Creep is a property of salt that causes it to deform and flow when exerted upon by unequal stresses (think “Silly Putty”)
- Salt, potash, cement are known to exhibit creep; most geological materials do not, or do so at much lower levels
- Salt is like water (and unlike most geological materials) in that the horizontal stresses at depth are equal to the vertical stress at depth due to overburden, called hydrostatic stress (most rocks have a lower horizontal stress due to elasticity)
- When a cavern is formed, the salt tries to move into the region of lower pressure to reach a hydrostatic stress state
- The oil/brine pressure cannot match the in situ (overburden) pressure in the salt; thus the salt creeps into the cavern.
- $\dot{\varepsilon} = A\left(\frac{\Delta\sigma}{G}\right)^{n} e^{\frac{-Q}{RT}}$; $\dot{\varepsilon}$ is strain rate, $\Delta\sigma$ is difference between horizontal, vertical stresses

Effects of creep



Primary effects

- Loss of cavern volume
- Tensile stresses/strains created in wellbore casings due to stretching
- Cavern floor rises

Secondary effects

- Surface subsidence
- Salt falls (created by extreme stress states, geometric anomaly)
- Shear in wellbore casings (particularly around perimeter of cavern field)
- Change in pressure in nearby caverns during workover