SAND2012-3068C
SAND2012-3068 C

Analyzing Large Pressure Changes on the Stability of Large-Diameter Caverns Using the M-D Model

Steven R. Sobolik and Brian L. Ehgartner

Sandia National Laboratories

Albuquerque, New Mexico, USA

7th Conference on the Mechanical Behavior of Salt: Paris, France

April 17, 2012

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

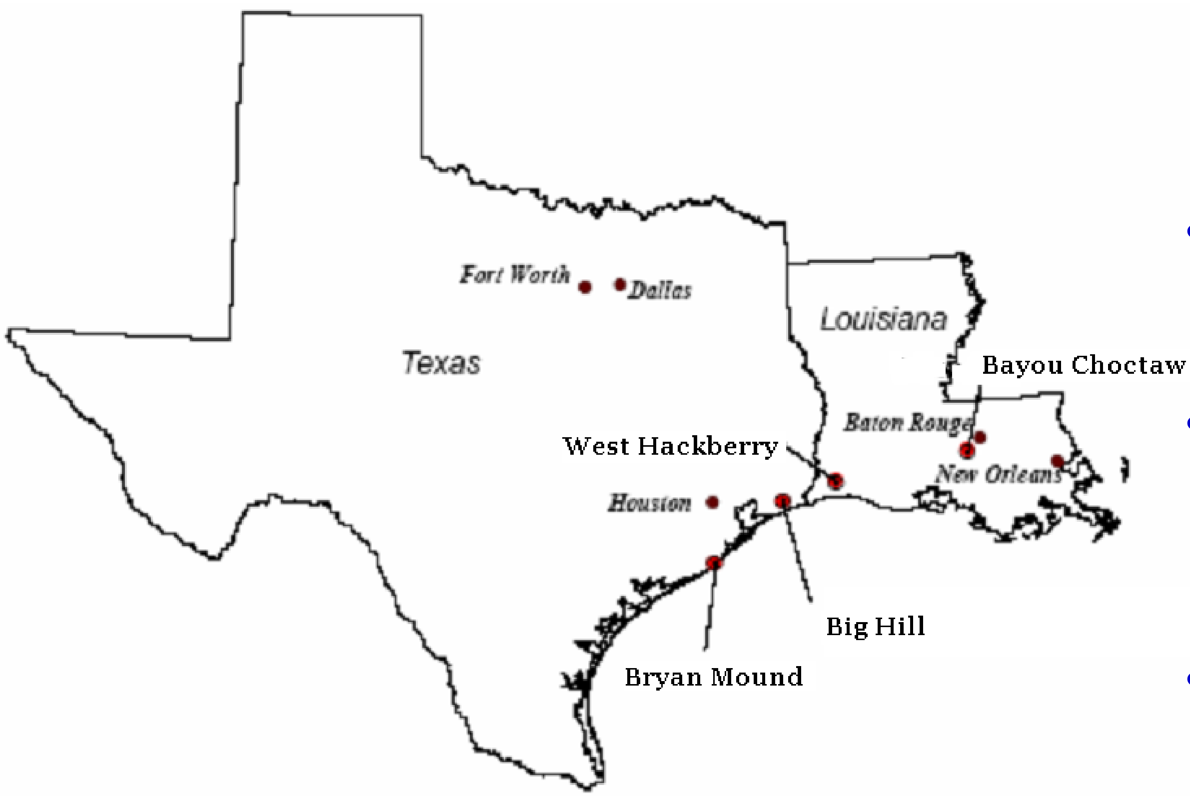
LOCKHEED MARTIN

Sandia National Laboratories

Today's Presentation

- Brief description of the caverns at the Strategic Petroleum Reserve's West Hackberry site
- Description of the event at West Hackberry Cavern 6, a large-diameter oil storage cavern
- History of previous geomechanical analyses of West Hackberry caverns
- Description of new analyses of Cavern 6 event and workover using the M-D model
- Results of the analyses and recommendations for completion of workover operations

West Hackberry SPR Site



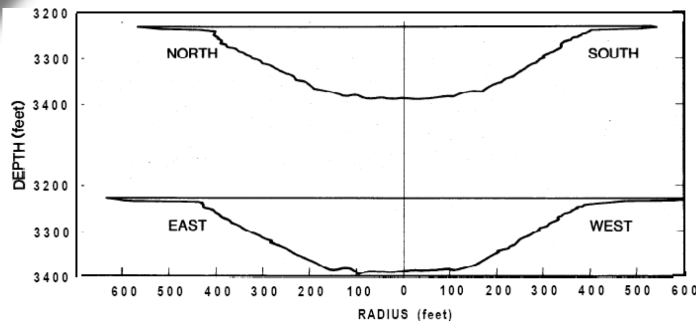
West Hackberry site includes:

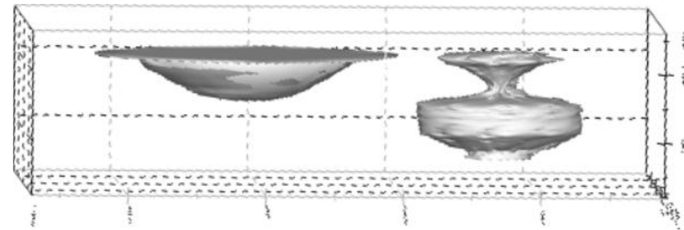
- **~228 MMB of oil storage.**
- **5 unusually-shaped, reasonably axisymmetric storage caverns (#6, 7, 8, 9, 11) built in 1940s-1950s.**
- **17 cylindrical-shaped storage caverns (#101-117) built in early 1980s.**
- **Approximately 480m sandstone overburden, 120 m anhydrite/carbonate caprock over salt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

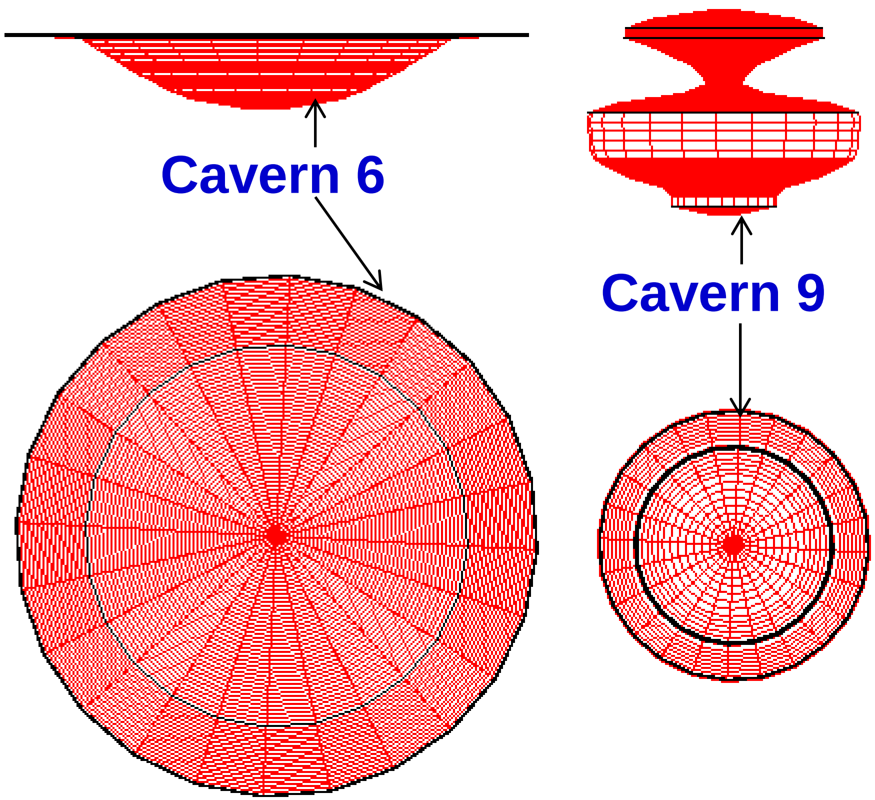
LOCKHEED MARTIN

Sandia National Laboratories

West Hackberry Caverns 6 and 9



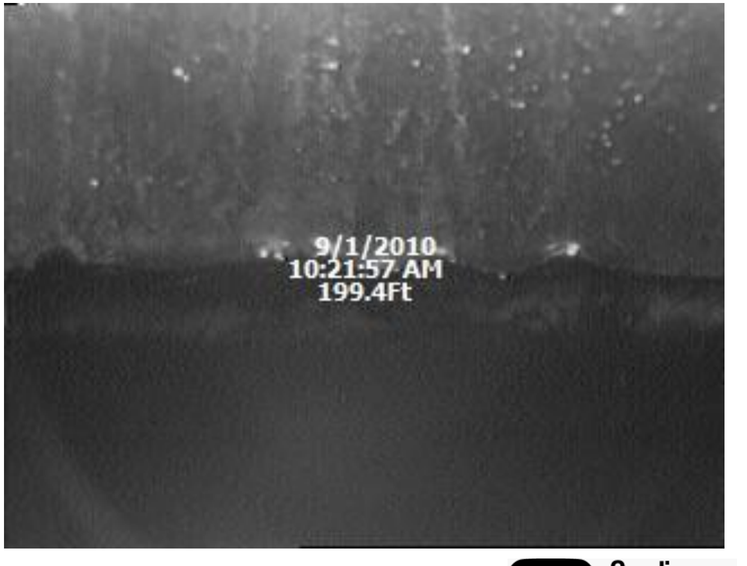




- Caverns 6, 9 originally made for brine production
- Bowl-shaped Cavern 6, 350-375 m diameter span
- Most recent sonar/strapping of Cavern 6 was in 1981.
- Tip of rim of cavern 6 approx. 70 m from upper lobe of cavern 9, 60 m from lower lobe, web thickness between caverns approx. 44 m
- Cavern 6 has 3 wells: 6b and 6c (lined due to earlier failures) and 6 (unlined before Sept. 2010)

Event at Cavern 9

- **Sep. 2010 multi-arm caliper log of Well 6 178-mm production casing found severe damage at 59 m, 777 m depths (apparent tensile failure).**
- **Decision made to plug and abandon well; workover begun Sep. 28, 2010, wellbore cemented to flange Jan. 5, 2011**
- **Because of concerns of tensile cracking around Cavern 6, analyses were performed to determine appropriate repressurization procedure.**



LOCKHEED MARTIN

Sandia National Laboratories

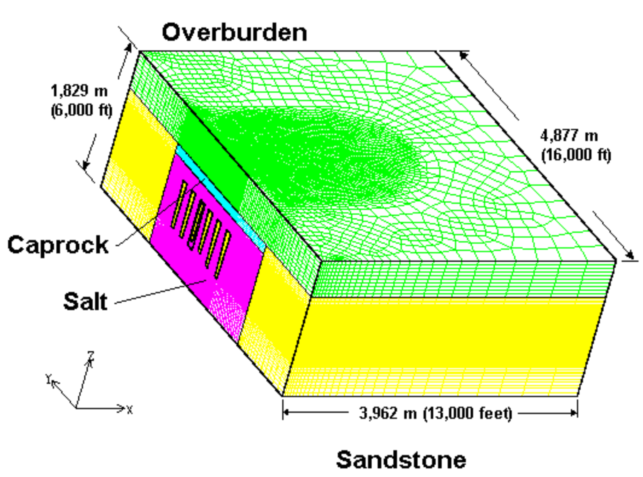
Results from Previous Analyses

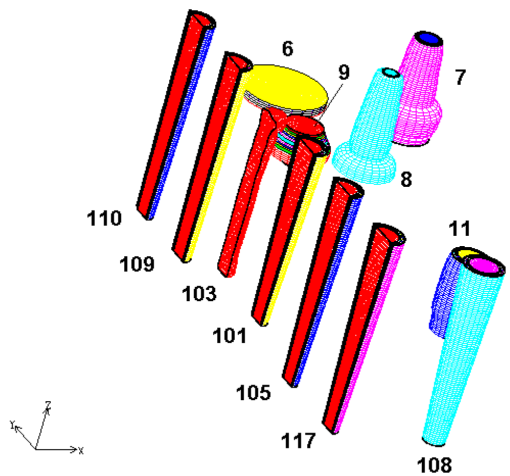
- Previous analyses (Sobolik and Ehgartner, 2009) used power-law creep model with reduced elastic modulus, producing exaggerated transient stress response.
- Because of dish-like shape of Cavern 6, perimeter of the cavern is at risk of dilatant and tensile damage, particularly at the end of a work-over operation.
- Close proximity of Cavern 9 poses a risk of inter-cavern communications.
- Recommendation that workovers performed on Cavern 9 wells be performed no sooner than one year after the completion of a workover in Cavern 6 to allow the stressed salt enough time to attain near-hydrostatic stress values, so to minimize the possibility of cracking the salt between Caverns 6 and 9.

New Analysis to Address Cavern 6 Workover

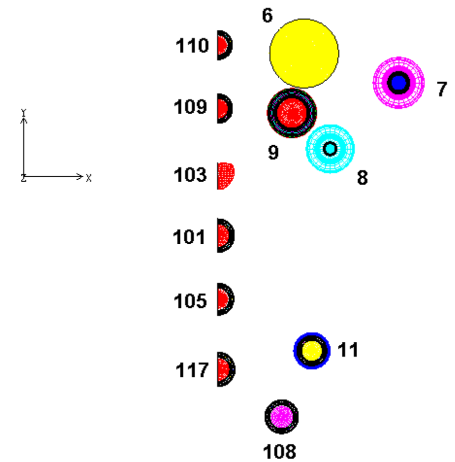
- Purpose of analysis was to recommend appropriate repressurization rate to prevent salt cracking, yet also minimize cavern volume loss during low-pressure state.
- Analysis used M-D model for accurate simulation of transient and primary creep mechanisms.
- Analysis evaluated different conditions of Cavern 6 rim, different repressurization rates.

West Hackberry Computational Mesh

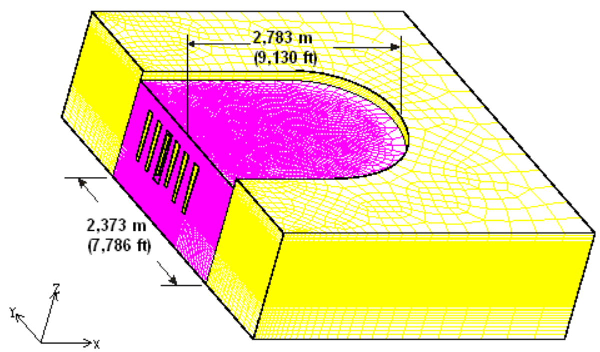




West Hackberry caverns, including five leachings (except for cavern 103)



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



- Vertical plane of symmetry along N-S axis
- 1.3M elements
- Calculations run on 32 parallel processors
- All M-D properties (M-D) from Sobolik et al. (2010).
- Standard operating pressures (6.20-6.72 MPa at wellhead), 5-year workover schedule

LOCKHEED MARTIN

Sandia National Laboratories

M-D Model

- The multi-mechanism deformation (M-D) model is a rigorous mathematical description of both transient and steady-state creep phenomena.
  - steady state creep rate
  - transient strain limit
  - work-hardening and recovery time rate of change (*i.e.,* curvature)
- Because of highly nonlinear nature of the transient strain response, M-D model has only recently been successfully integrated in full 3-D calculation for a model with millions of elements (Sobolik, Bean, & Ehgartner, 2010).

LOCKHEED MARTIN

Sandia National Laboratories

M-D Model Formulation

Steady state strain rates

$$\dot{\varepsilon}_s = \sum_{i=1}^{3} \dot{\varepsilon}_{s_i}$$

$$\dot{\varepsilon}_{s_1} = A_1 \left(\frac{\sigma_{eq}}{G} \right)^{n_1} e^{\frac{-Q_1}{RT}}$$

$$\dot{\varepsilon}_{s_2} = A_2 \left(\frac{\sigma_{eq}}{G} \right)^{n_2} e^{\frac{-Q_2}{RT}}$$

$$\dot{\varepsilon}_{s_3} = \left(B_1 e^{-Q_1/RT} + B_2 e^{-Q_2/RT} \right) *$$

$$\sinh\left[q \left(\frac{\sigma_{eq} - \sigma_0}{G} \right) \right] H\left(\sigma_{eq} - \sigma_0\right)$$

Transient effects

$$\dot{\varepsilon}_{eq} = F \dot{\varepsilon}_s$$

$$F = \begin{cases} \exp\left[\Delta \left(1 - \frac{\zeta}{\varepsilon_t^f} \right)^2 \right] & \zeta < \varepsilon_t^f \quad \text{Transient Branch} \\ 1 & \zeta = \varepsilon_t^f \quad \text{Equilibrium Branch} \\ \exp\left[-\delta \left(1 - \frac{\zeta}{\varepsilon_t^f} \right)^2 \right] & \zeta > \varepsilon_t^f \quad \text{Recovery Branch} \end{cases}$$

$$\varepsilon_t^f = K_0 e^{cT} \left(\frac{\sigma_{eq}}{G} \right)^m$$

Transient strain limit

$$\dot{\zeta} = (F - 1) \dot{\varepsilon}_s$$

Internal variable, ζ

$$\Delta = \alpha + \beta \log\left(\frac{\sigma_{eq}}{G} \right) \qquad \delta = \alpha_\gamma + \beta_\gamma \log\left(\frac{\sigma_{eq}}{G} \right)$$

LOCKHEED MARTIN

Sandia National Laboratories

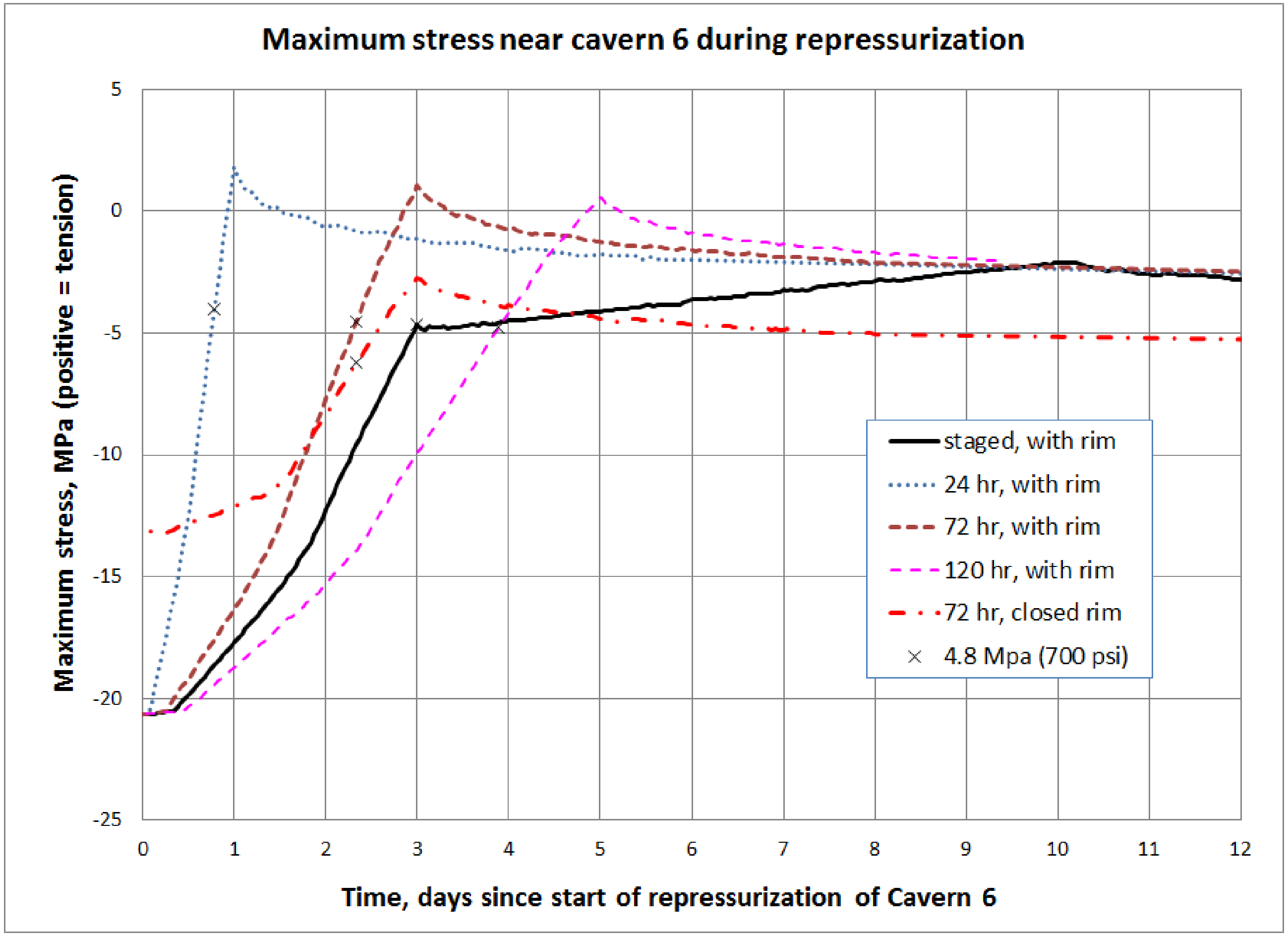
Unknown Condition of Cavern 6 Rim

- The current condition of the rim of Cavern 6 is not known (last sonar in 1981).
- Therefore, there are three probable current conditions of the rim around Cavern 6:
  - Highly compressed, but still enough oil in it to allow pressure communication from the main cavern out to the edge of the rim
  - Completely pinched off at the edge of the main part of the cavern (i.e., no more rim)
  - Pinched off somewhere between the main cavern and the original rim edge
- Calculations assume either full rim or no rim as current condition.

Analysis Scenarios

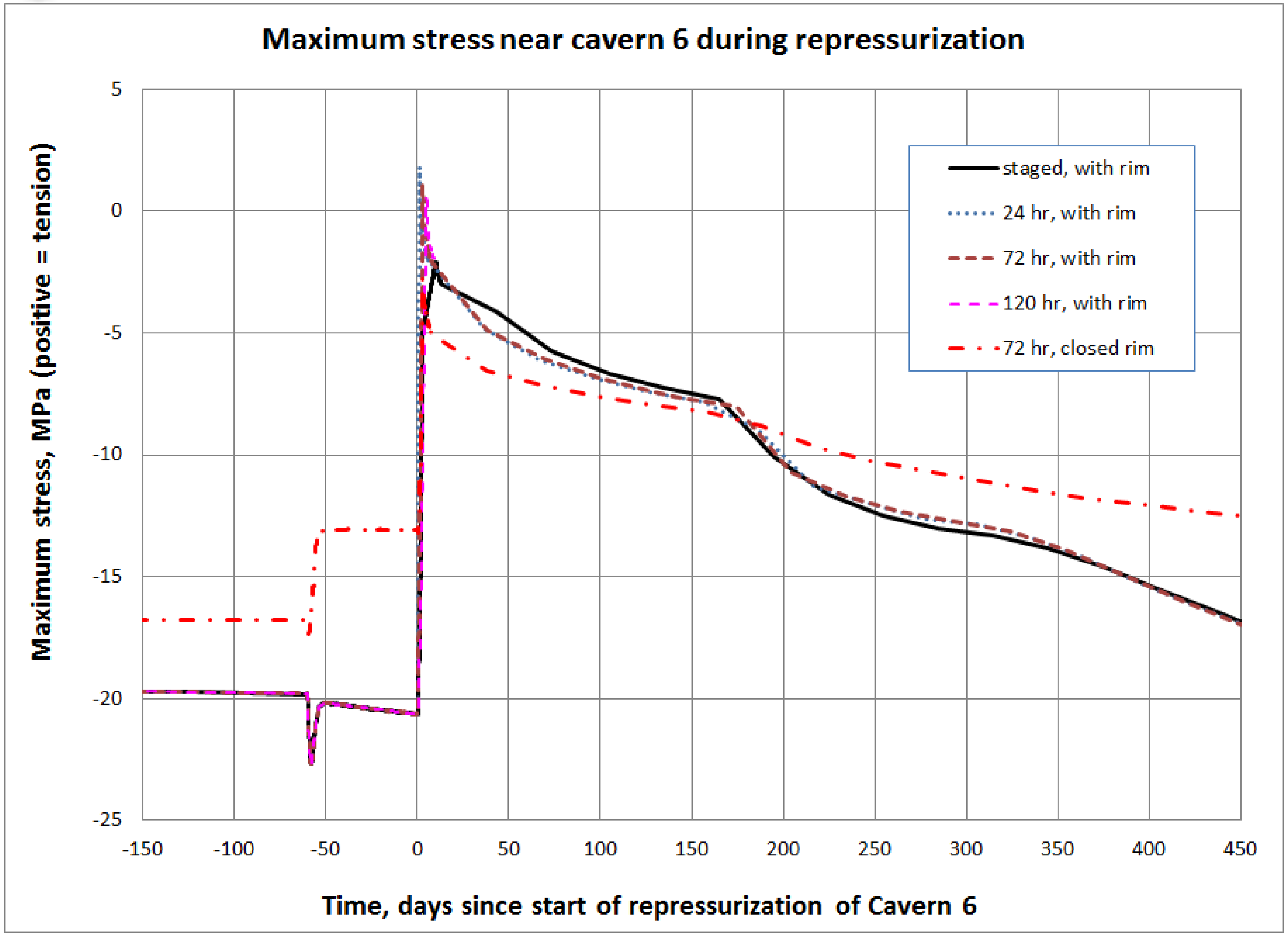
- **Wellhead pressure in Cavern 6 was dropped from operating pressure of 6.2 MPa to 0 for workover in 5 days, held for additional 55 days before repressurization. Five scenarios were simulated:**
  - **Cavern with rim, raise wellhead pressure from 0 to 6.2 MPa in 24 hours (1 day).**
  - **Cavern with rim, raise wellhead pressure from 0 to 6.2 MPa in 72 hours (3 days).**
  - **Cavern with rim, raise wellhead pressure from 0 to 6.2 MPa in 120 hours (5 days).**
  - **Cavern with closed rim, raise wellhead pressure from 0 to 6.2 MPa in 72 hours (3 days).**
  - **Cavern with rim, with staged repressurization: raise wellhead pressure from 0 to 4.8 MPa in 72 hours (3 days), followed by 7-day period raising the pressure to 5.9 MPa.**

Maximum stress during repressurization



- Cases with rim, steady pressure rise reach tensile stress on rim at maximum pressure
- Case with closed rim predict no tension, differing from PLC results.
- Case with staged pressure rise does not reach tensile stresses at the rim or elsewhere.

Maximum stress 1 year later

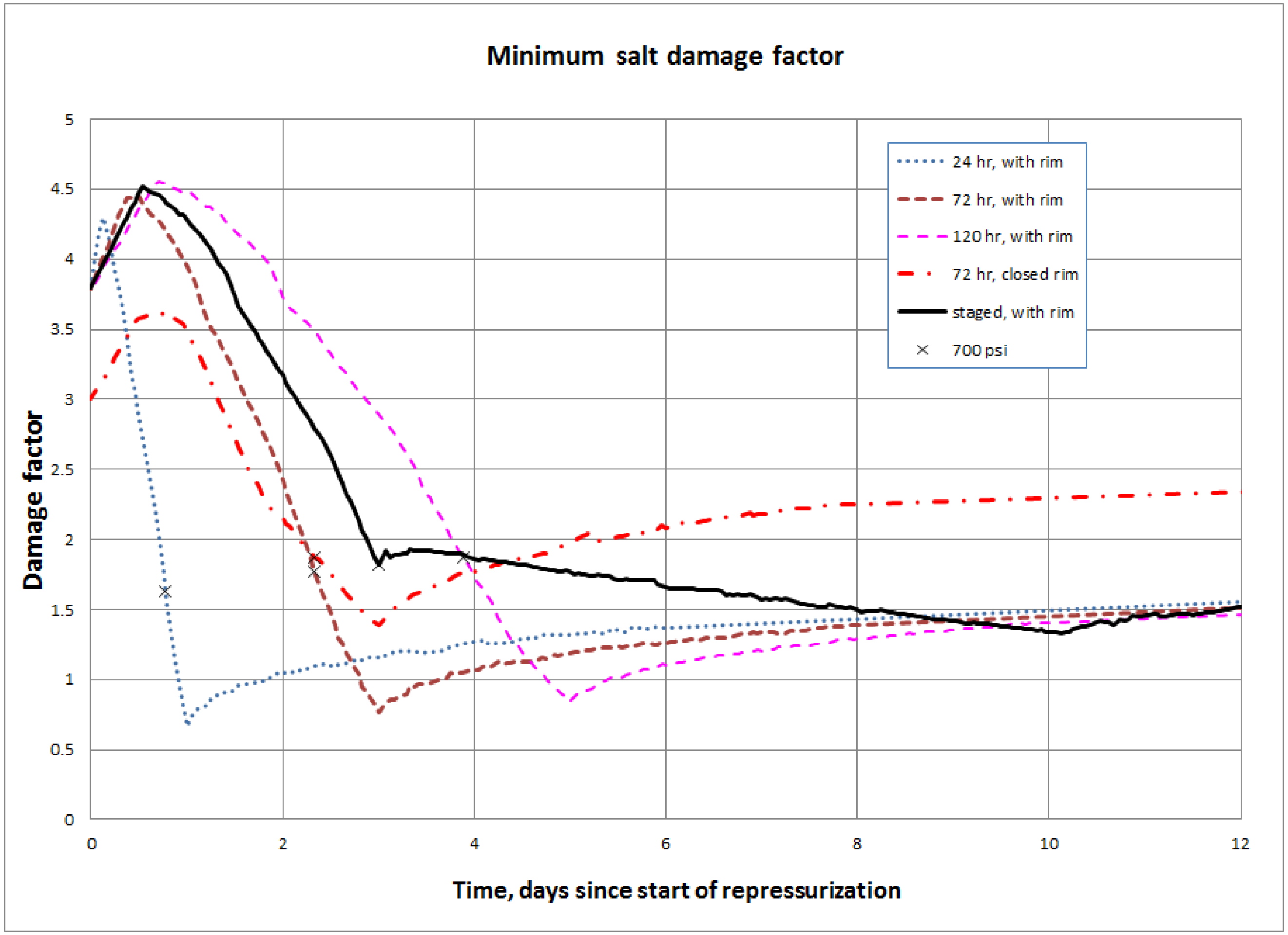


- **Maximum stress has not reached in situ value by 450 days.**
- **Because of the proximity of Cavern 9, this reinforces the recommendation to wait at least one year between workovers of Caverns 6 and 9.**

LOCKHEED MARTIN

Sandia National Laboratories

Minimum salt damage factor near Cavern 6



- **Damage factor based on dilatant stress criterion**

$$\sqrt{J_2} = 0.27 I_1$$

- **Damage factor < 1 indicates onset of damage.**
- **Staged pressure rise keeps damage factor above 1.3 at maximum pressure; all other scenarios with a rim reach damage threshold.**

LOCKHEED MARTIN

Sandia National Laboratories

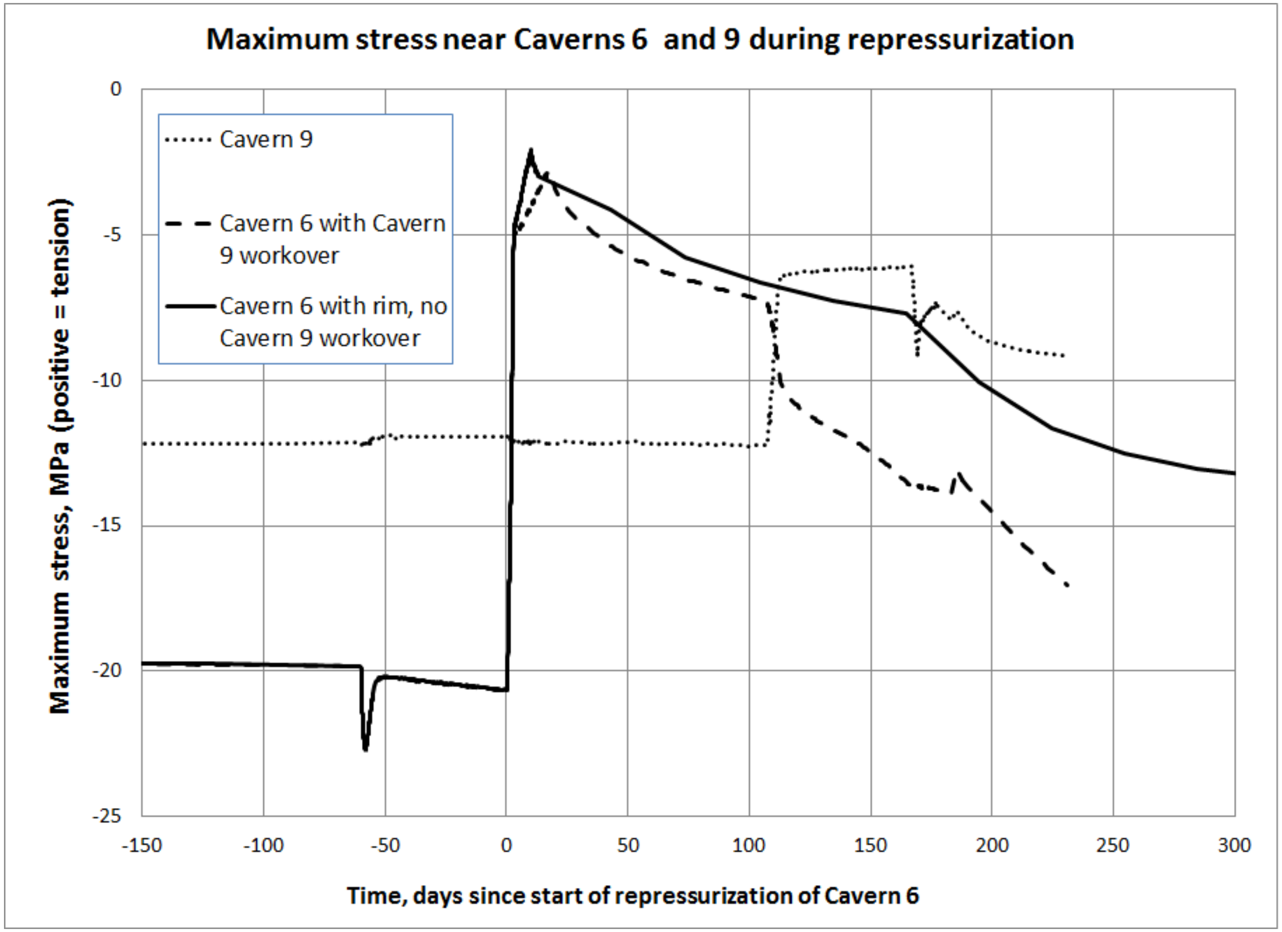
Completion of Cavern 6 Workover

- Following the completion of wellbore cementing on January 5, 2011, repressurization of the cavern started on January 14, 2011 based on staged repressurization.
- Wellhead pressure in Cavern 6 was raised to 4.8 MPa over three days, followed by an additional 14-day period to raise the wellhead pressure to the low end of its normal operating range, 5.9 MPa on January 31, 2011.
- Based on all indications from well pressure measurements from Caverns 6 and 9, there has been no event indicative of additional well damage or loss of cavern integrity since the workover was completed.

Additional Analyses for Cavern 9

- Earlier analyses recommended that workovers performed on Cavern 9 should be performed no sooner than one year after the completion of a workover in Cavern 6.
- To address additional concerns about the interactions between Caverns 6 and 9, additional set of calculations were proposed:
  - A workover procedure on Cavern 9 that would begin three months after the completion of the recent Cavern 6 procedure.
- Simulated workover on Cavern 9 began 107 days after the beginning of Cavern 6 repressurization, with 5-day decrease to 0 wellhead pressure. After 60 days (Day 167), pressure was raised to 4.8 MPa over 3 days, then to 5.9 MPa over 7 days (to Day 177), held for another 8 days until raised to its original wellhead pressure of 6.38 MPa.

Maximum stress near Caverns 6, 9

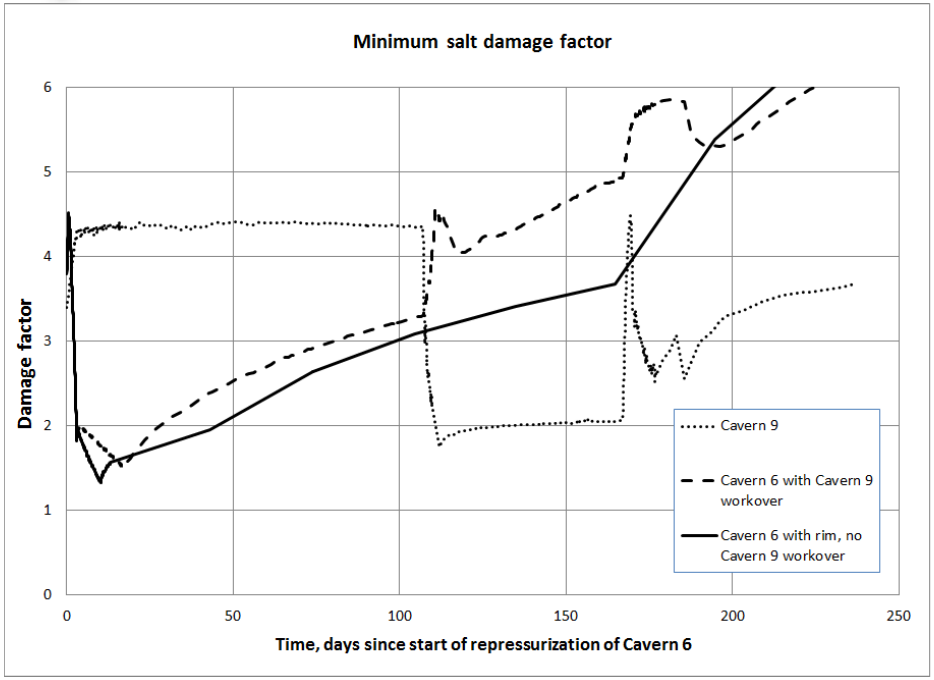


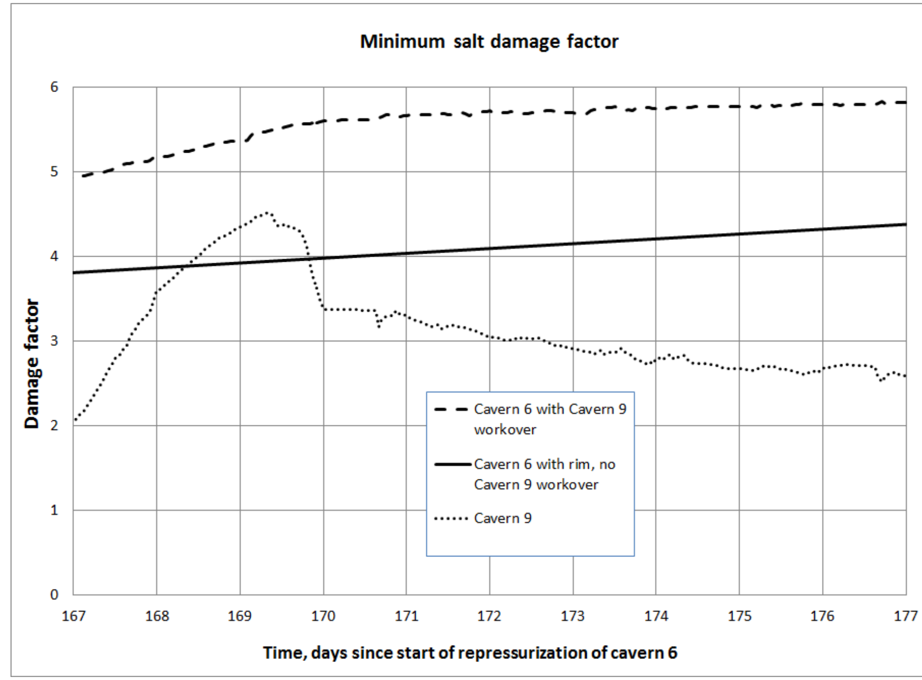
- Maximum stress around Cavern 9 occurs in the "ledge", the circular structure projecting into the middle of the cavern.
- Neither cavern experiences tensile stress during these operations.
- Workover on Cavern 9 actually helps the edge of Cavern 6 reach steady state stress more quickly.

LOCKHEED MARTIN

Sandia National Laboratories

Minimum damage factor near Caverns 6, 9





- **Workover on Cavern 9 seems to accelerate how quickly the edge of Cavern 6 returns to a steady-state, low-shear stress.**
- **Cavern 9 sees reversal of trend part of the way through the repressurization period (Days 167 to 177).**
- **Recommended ta similar staged approach to repressurizing Cavern 9 so as not to bring the ledge to dilatant stress values.**

LOCKHEED MARTIN

Sandia National Laboratories

Conclusions

- Computational model for West Hackberry SPR site is mature, with a mesh containing realistic geometries for the caverns and salt dome, a functional M-D model, and operating pressure scenarios that can be modified to fit current and new scenarios.
- This report demonstrates the capability to apply complex, three-dimensional geomechanical computations to make recommendations to field operations in a short time frame.
- Previous analyses predicted casing failure for Well 6.
- Procedure recommended by these analyses insured safe repressurization of Cavern 6.
- Additional analyses in this report demonstrate the capability to anticipate potential problems that may occur in the field, and plan operational procedures to prevent or mitigate negative consequences.

LOCKHEED MARTIN

Sandia National Laboratories

Extra Slides

Advantages of M-D Model

Model	Pros	Cons
Power Law Creep with reduced E	• Numerically more stable • Ability to attain good agreement in long-term predictions of cavern closure, surface subsidence • Properties available from lab tests	• Does not physically represent short-term, large ΔP events (workover, gas cycling, etc.) • Requires calibration of creep coefficient based on field data
M-D Model	• Model captures transient, separate steady-state components of creep, better suited to modeling short-term, large ΔP events • Properties available with larger suite of lab tests • Should require less post-site adjustment of properties with field data	• Transient component introduces numerical stability problems • Greater CPU time • Availability of sufficient lab data for all model properties

Enhanced Numerical Integration Scheme

- Allow choice of forward Euler or backward Euler integration based on global time step required for stability.
- Backward Euler integration employs Newton-Raphson solver.
- Deviatoric stress s_{ij} and evolution variable ζ tensors solved in integration routine.