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Effects of Cavern Shapes on Cavern and Well Integrity for the Strategic Petroleum Reserve

Steven R. Sobolik and Brian L. Ehgartner

Sandia National Laboratories

Albuquerque, New Mexico, USA

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Background

- Most cavern field designs are based on a pillar-to-diameter (P/D) ratio and assumed cylindrical cavern shapes
  - Many sites are characterized by a cavern field of reasonably uniform cavern dimensions (radius, height, shape, and depth) and spacing (e.g., Big Hill).
  - Other sites, such as Bayou Choctaw, are characterized by diverse cavern characteristics.
- Unusual cavern shapes created either by design, variability in salt properties, or by happenstance.

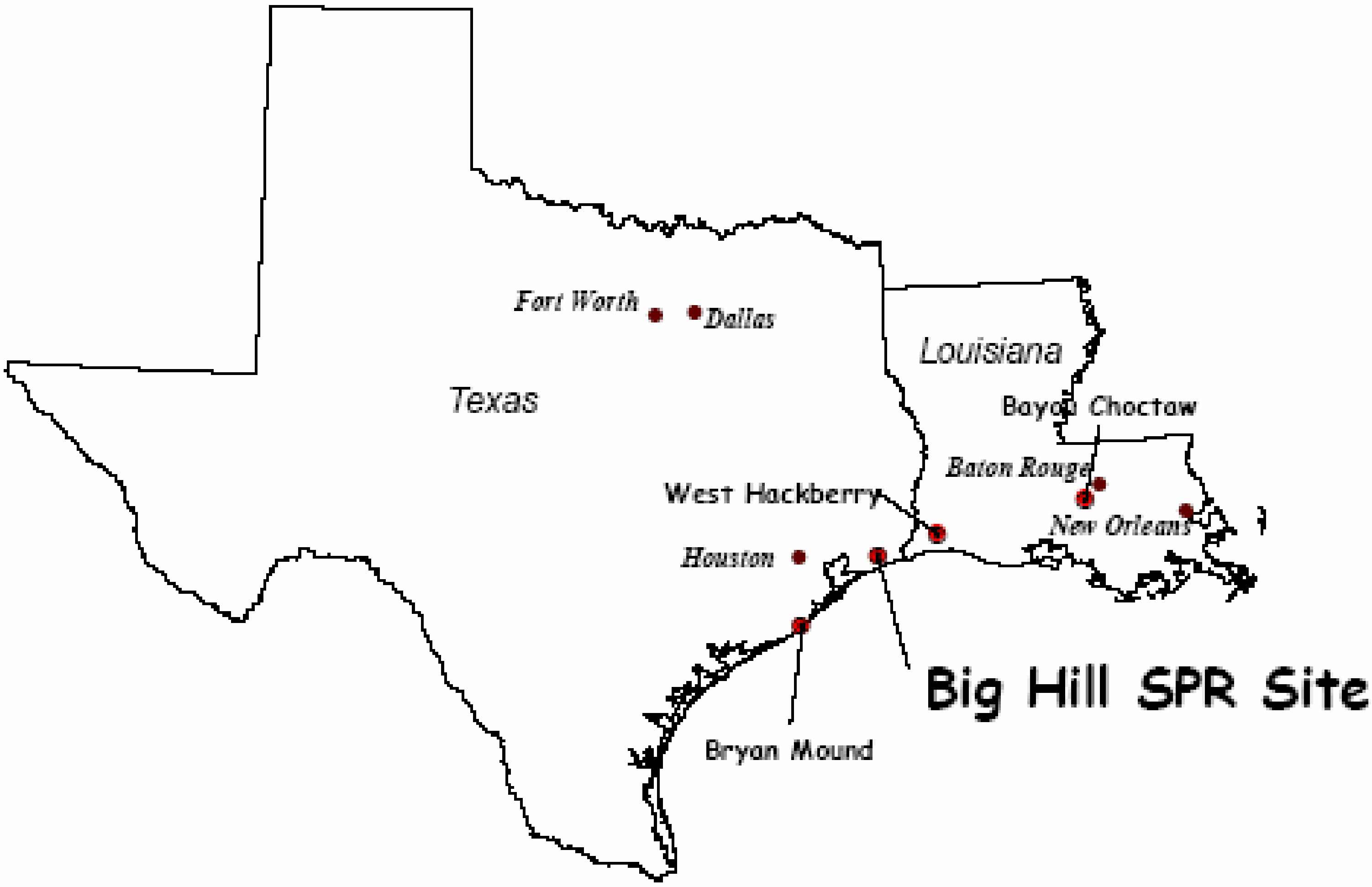
Background

- The Energy Policy Act of 2005 calls for expanding the SPR from ~700 to ~1000 MMB
  - Expand existing caverns
  - Add caverns to existing site
  - Develop new storage sites.
- Current DOE mandate that pillar-to-diameter ratio (P/D) between caverns must be greater than 1.78, based on pre-1983 analyses.

Objectives of Analysis

- Determine the structural integrity of different salt cavern shapes.
  - Four cavern shapes – cylindrical, enlarged tops, enlarged middles, enlarged bottoms
  - Volumes based on cavern radii from 100 to 300 feet
- Predict cavern performance and damage in salt based on four design factors.
  - Dilatant damage in salt
  - Cavern volume closure
  - Axial well strain in the caprock
  - Surface subsidence

Big Hill Salt Dome, Texas



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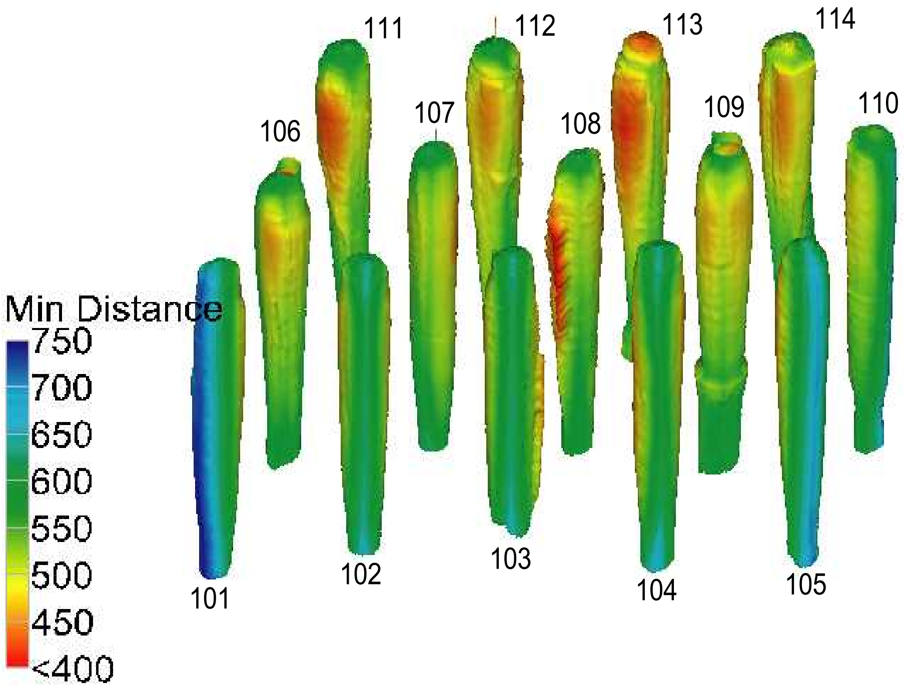
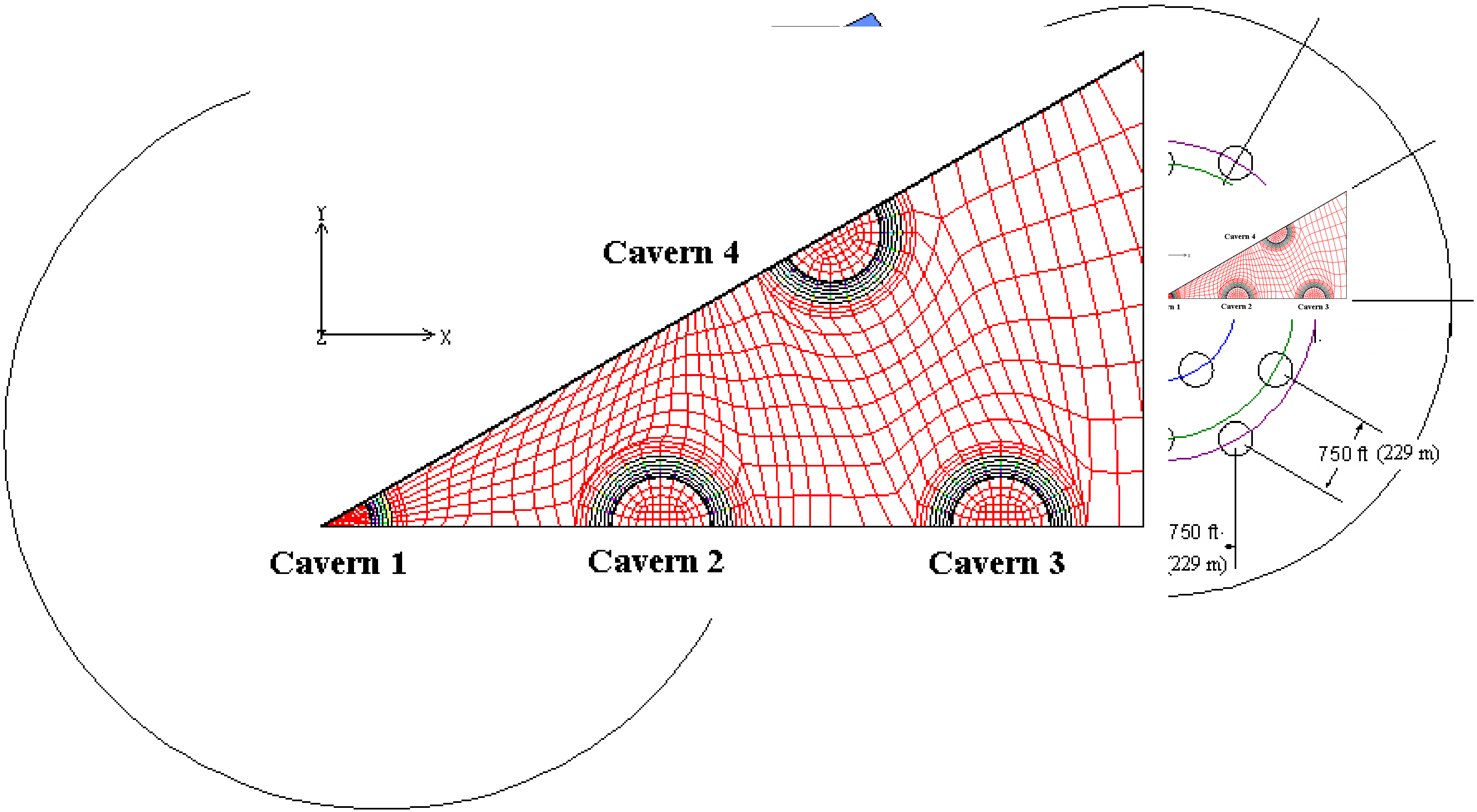
Big Hill Cavern Shapes

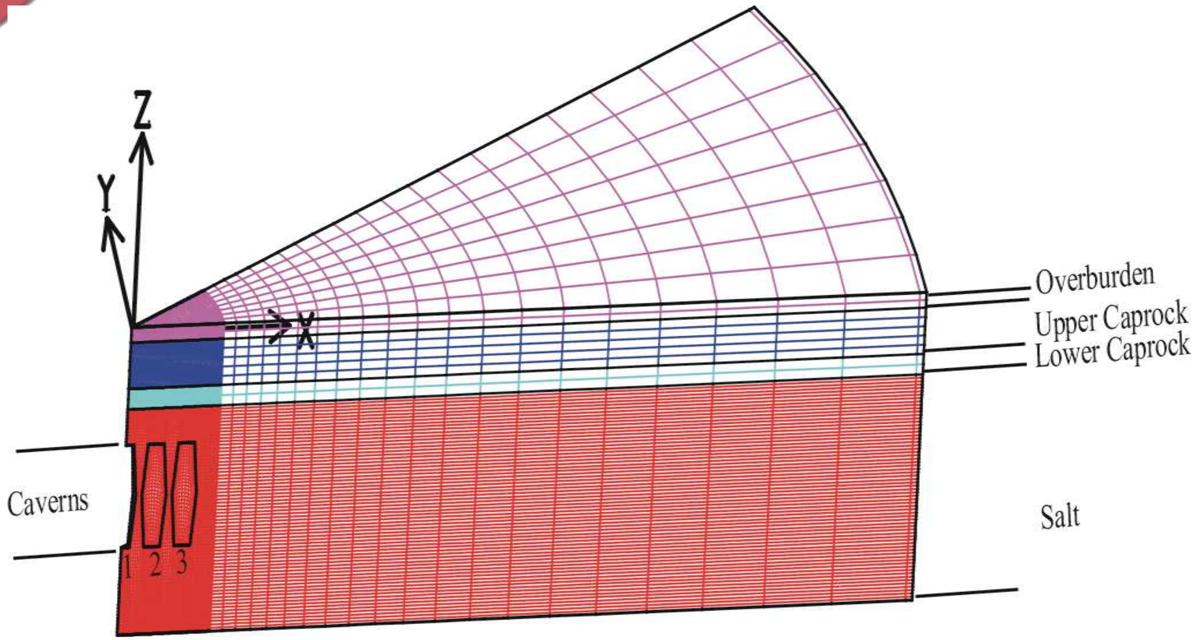


- Intentionally shaped initially with larger tops to accommodate future oil drawdowns where the bottom portions of the caverns are preferentially leached, and hence the overall cavern shape becomes more cylindrical
- Greater diversity in cavern shapes/sizes at other SPR sites

3-D View of recent cavern sonars at Big Hill

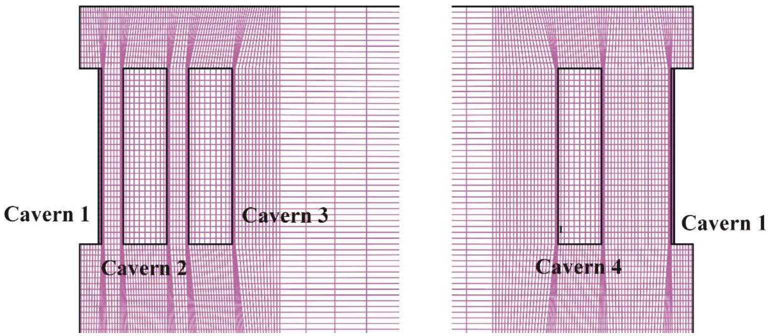
Modeling Approach – 19-Caverns Field



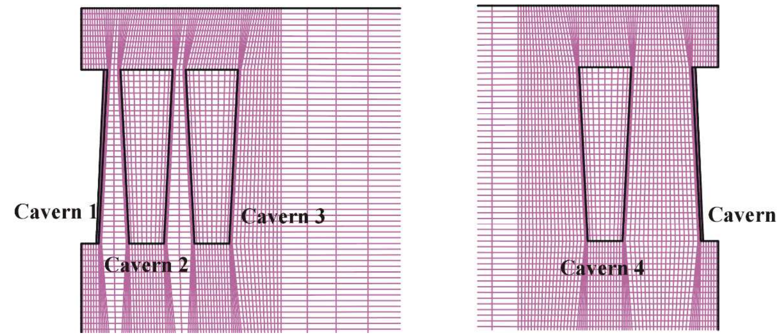


Dimension	Length
Well depth (surface to top of cavern)	701.0 m (2300 ft)
Initial cavern spacing	228.6 m (750 ft) center-to-center
Initial cavern height	576 m (2000 ft)
Depth to top of salt layer	487.7 m (1600 ft): 91.44 m (300 ft) overburden, 274.3 m (900 ft) upper caprock 121.9 m (400 ft) lower caprock

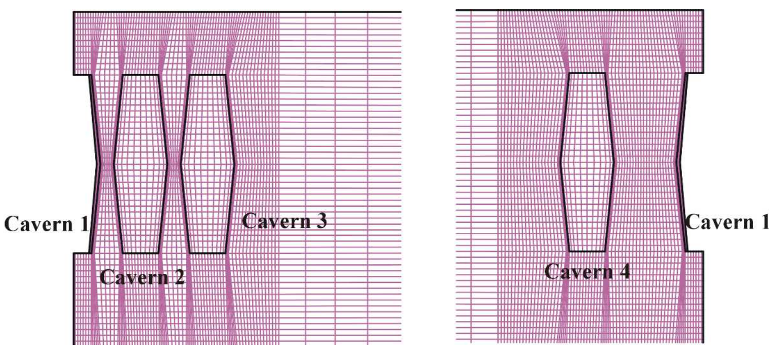
Modeled Cavern Shapes



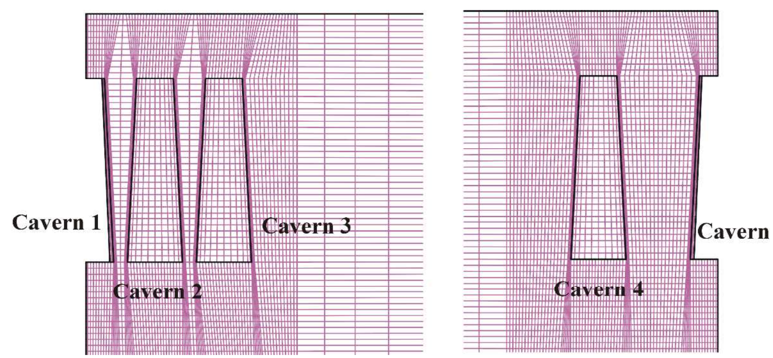
Cylindrical Caverns



Enlarged-Top Caverns



Enlarged-Middle Caverns



Enlarged-Bottom Caverns

(Cases shown here for 250-feet base radius)

Description of 17 Test Cases

Cavern shape case		Radius at heights (all lengths in feet)			Volume, MMB	P/D at heights			Min. P/D	Avg. P/D	Level III P/D
Name	Base radius	0	1000	2000		0	1000	2000			
Cylindrical caverns											
cyl100	100	100	100	100	11.19	2.75	2.75	2.75	2.75	2.75	2.75
cyl150	150	150	150	150	25.18	1.5	1.5	1.5	1.5	1.5	1.5
cyl200	200	200	200	200	44.76	0.875	0.875	0.875	0.875	0.875	0.875
cyl250	250	250	250	250	69.94	0.5	0.5	0.5	0.5	0.5	0.5
cyl300	300	300	300	300	100.72	0.25	0.25	0.25	0.25	0.25	0.25
Caverns with enlarged bottom diameter											
bot100	100	150	100	50	12.12	1.5	2.75	6.5	1.5	3.12	2.25
bot150	150	200	150	100	26.11	0.875	1.5	2.75	0.875	1.60	1.17
bot200	200	250	200	150	45.70	0.5	0.875	1.5	0.5	0.92	0.63
bot250	250	300	250	200	70.88	0.25	0.5	0.875	0.25	0.52	0.30
Caverns with enlarged middle diameter											
mid100	100	50	150	50	12.12	6.5	1.5	6.5	1.5	3.12	2.25
mid150	150	100	200	100	26.11	2.75	0.875	2.75	0.875	1.60	1.17
mid200	200	150	250	150	45.70	1.5	0.5	1.5	0.5	0.92	0.63
mid250	250	200	300	200	70.88	0.875	0.25	0.875	0.25	0.52	0.30
Caverns with enlarged top diameter											
top100	100	50	100	150	12.12	6.5	2.75	1.5	1.5	3.12	2.25
top150	150	100	150	200	26.11	2.75	1.5	0.875	0.875	1.60	1.17
top200	200	150	200	250	45.70	1.5	0.875	0.5	0.5	0.92	0.63
top250	250	200	250	300	70.88	0.875	0.5	0.25	0.25	0.52	0.30

Approach

- Computational Model
  - JAS3D, 3D FEM structural analysis code, is used for this study
  - 19-cavern model chosen to represent cavern field; hexagonal symmetry planes, with an interior angle of 30°
  - Simulate 45 years of operating/workover cycles; no leaching of caverns during simulation
  - Use stratigraphy, material properties of Big Hill
  - Power law creep model used for salt
- Assumptions
  - Stratigraphic materials strongly interlocked to each other
  - Omit sandstone surrounding the dome
  - Perform calculations without cement liner/steel casing – allow parametric study under simplified conditions
  - Future calculations to add cement, steel

Approach (continued)

- Internal Pressure in the Caverns
  - The simulated caverns were assumed to be leached to full size over one year to a brine pressure, then switched to operating pressure with oil.
  - Both normal cavern operating conditions and workover conditions were simulated.
  - For both normal and workover conditions, the caverns are assumed to be full of oil (a pressure gradient of 0.37 psi/ft of depth).
  - For normal operating conditions, the cavern pressure is based on a wellhead pressure of 945 psi, which is considered typical for BH caverns.
  - For workover conditions, zero wellhead pressure is used – workovers conducted for 3-month period every five years, rotating among caverns.

Power Law Creep Model

- **Power law creep – plastic strain rate a function of stress, temperature:**

$$\dot{\varepsilon} = A_2 \left(\frac{\sigma}{\mu} \right)^n \exp\left(-\frac{Q}{RT} \right) = A(\sigma)^n \exp\left(-\frac{Q}{RT} \right), \quad A = \frac{A_2}{\mu^n}$$

where, $\dot{\varepsilon}$ = creep strain rate,
σ = effective or von Mises stress,
μ = shear modulus, E/2(1+n) (E=Young's modulus, n=Poisson's ratio),
T = absolute temperature,
$A2$, A, n = constants determined from fitting the model to creep data,
Q = effective activation energy, and
R = universal gas constant.

Property for Big Hill Salt (Park et al., 2005)	Value
Density, kg/m^3	2300
Elastic modulus, GPa	2.48
Bulk modulus, GPa	1.65
Shear modulus, GPa	0.992
Poisson's ratio	0.25
Creep Constant A, 1/(Pa^n-sec)	8.69×10^{-38}
Exponent n	4.9
Thermal constant Q/R, K	6034

$$SF_{VS} = \frac{0.27 I_1}{\sqrt{J_2^{'}}}$$

Salt Damage Criteria

- **Van Sambeek (1993):**
  - **Dilatant damage criterion defined by linear function relating shear stress to hydrostatic pressure**

$$\sqrt{J_2} = 0.27 I_1 \qquad J_2, I_1 = \text{Stress Invariants}$$

- **Safety factor SF_{VS} based on damage criterion:**

$$SF_{VS} = \frac{0.27 I_1}{\sqrt{J_2^{'}}}$$

for which $SF_{VS} \leq 1$ indicates damage, $SF_{VS} \leq 0.6$ failure

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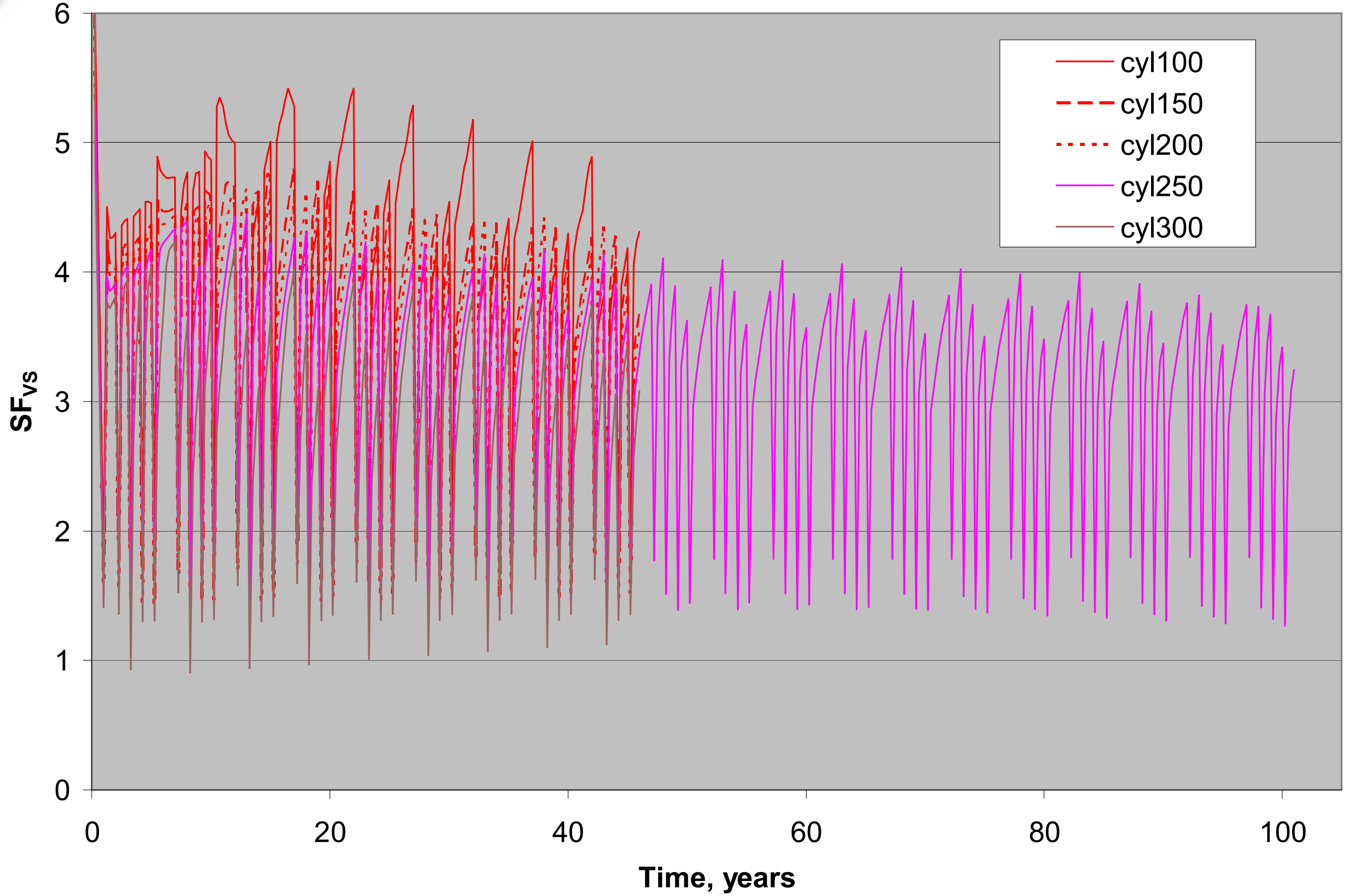
Minimum Safety Factor, Cylindrical Caverns



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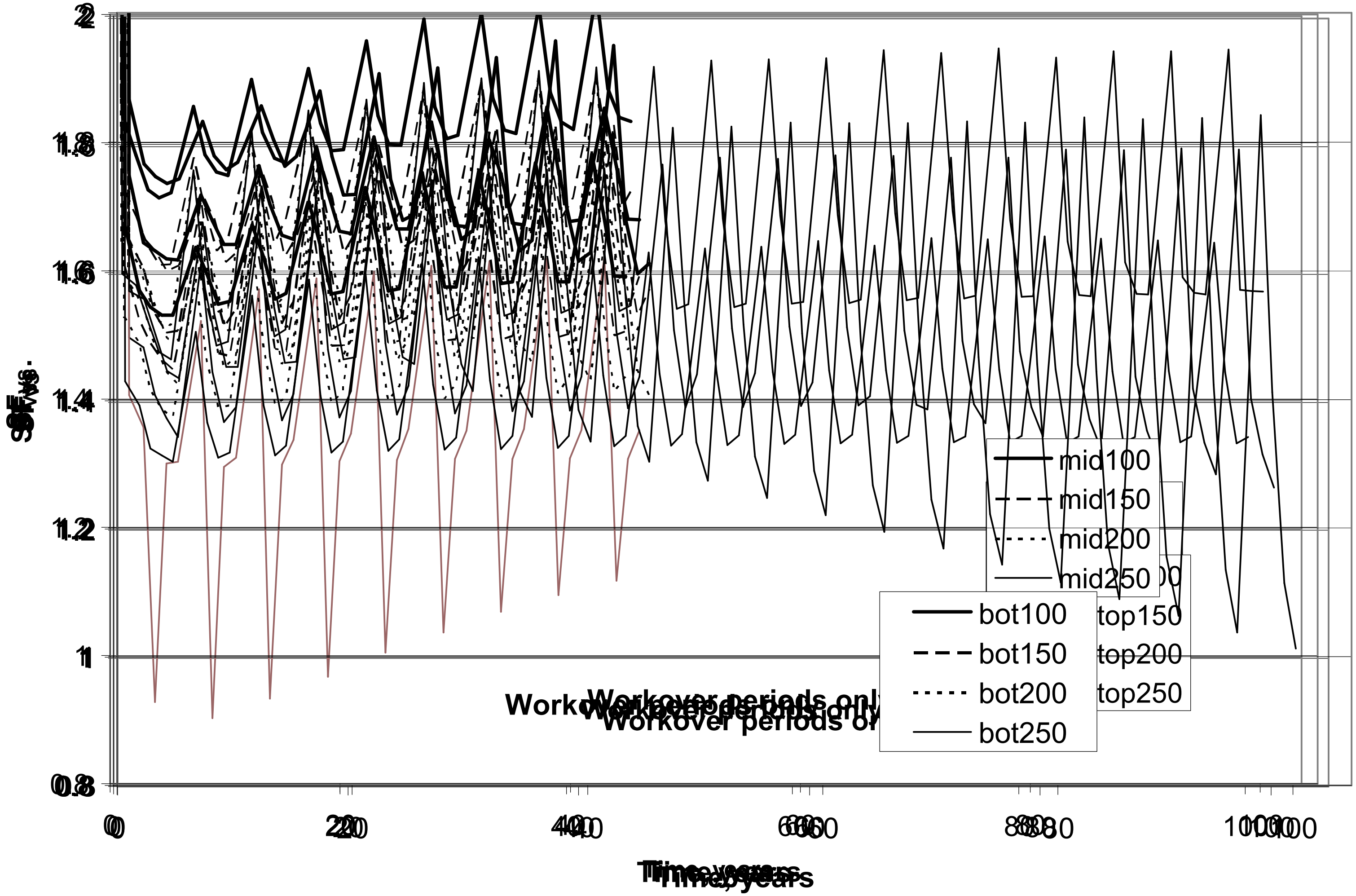
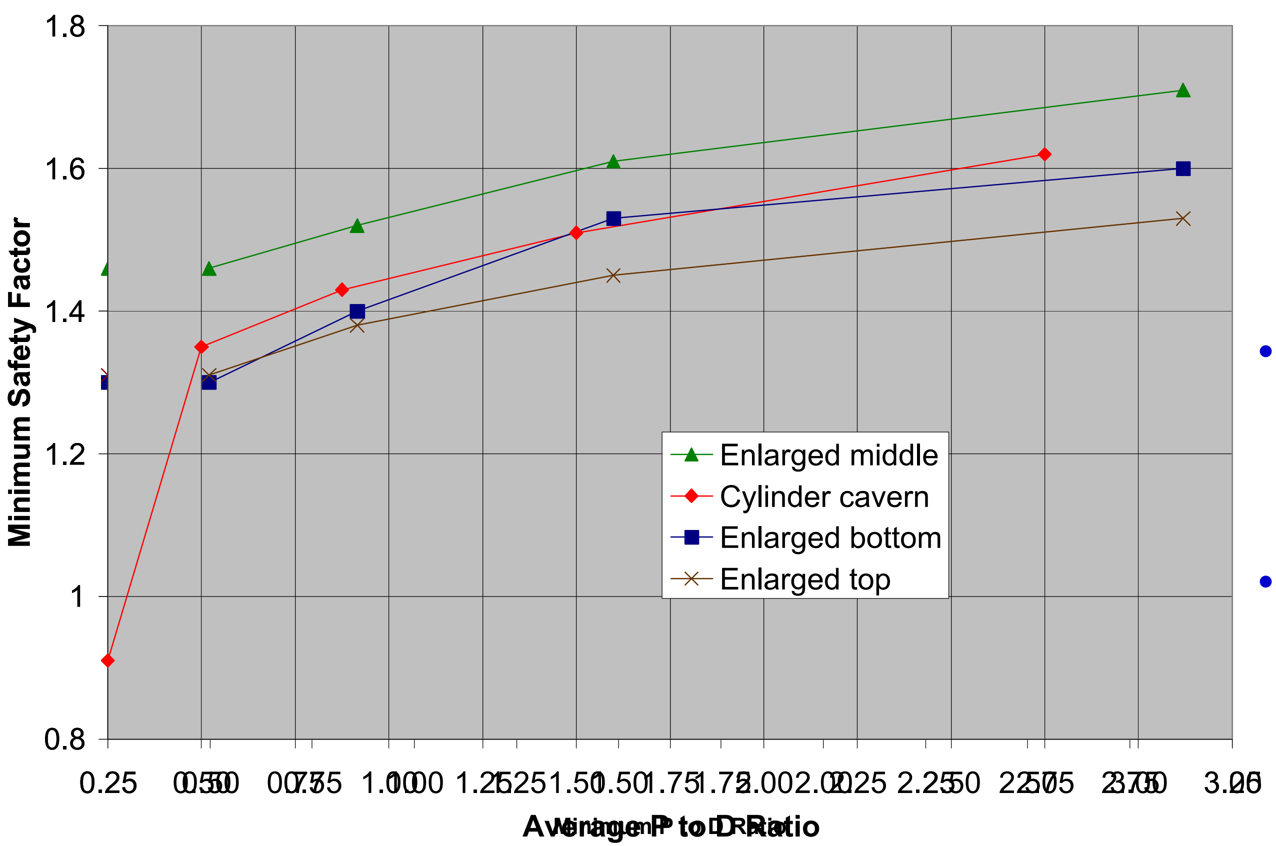
Minimum Safety Factors, Workover Periods



Minimum Safety Factor



Rank order (Best to Worst):

1) **Enlarged middle**
2) **Cylindrical**
3) **Enlarged bottom**
4) **Enlarged top**

- **Average P/D preferred to minimum P/D; relates caverns of similar volumes.**
- **Caverns with enlarged middles can have three times the volume as enlarged-top caverns, and still have equiv. min. safety factors, with smaller P/D ratio.**

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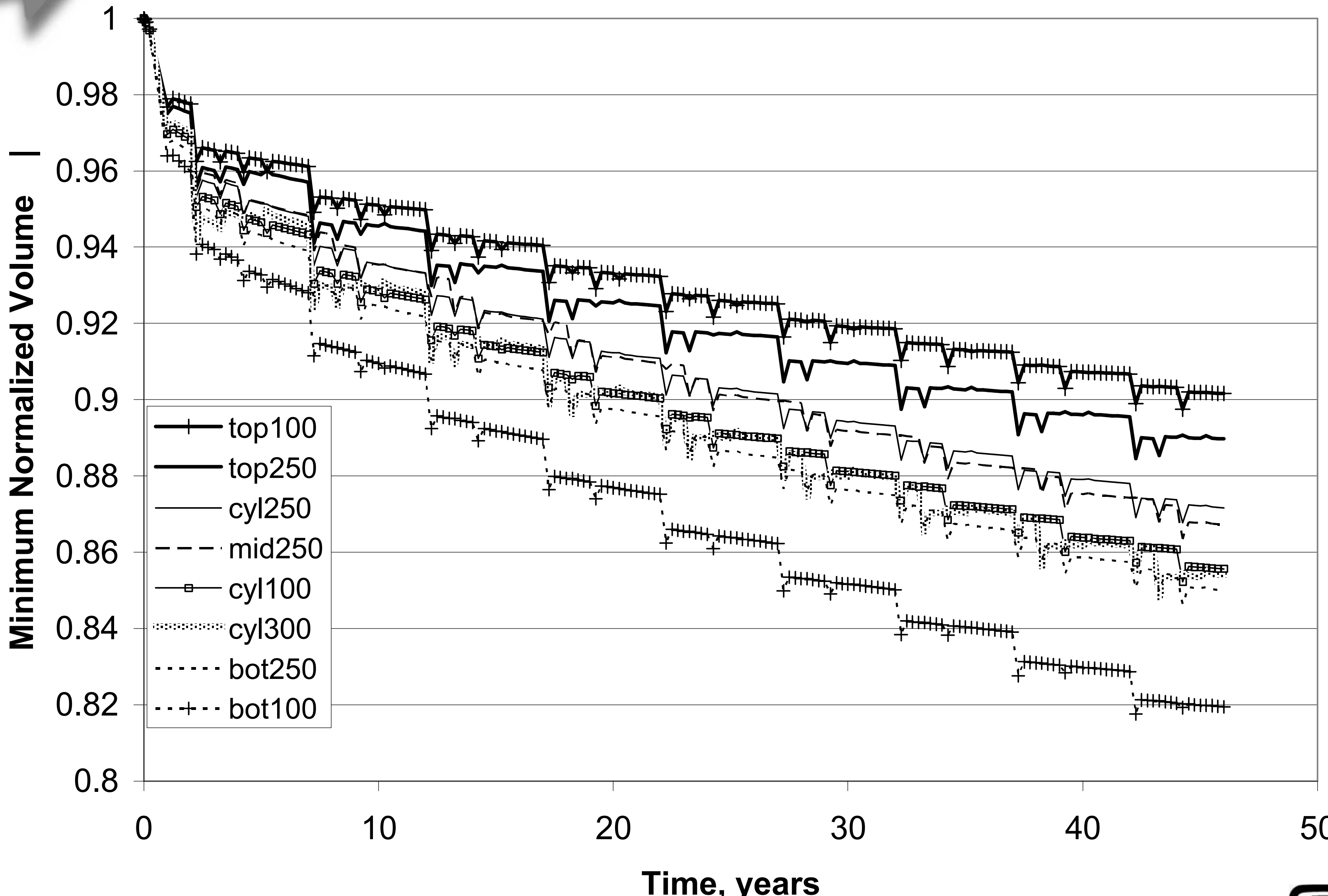
Cavern Volume Closure



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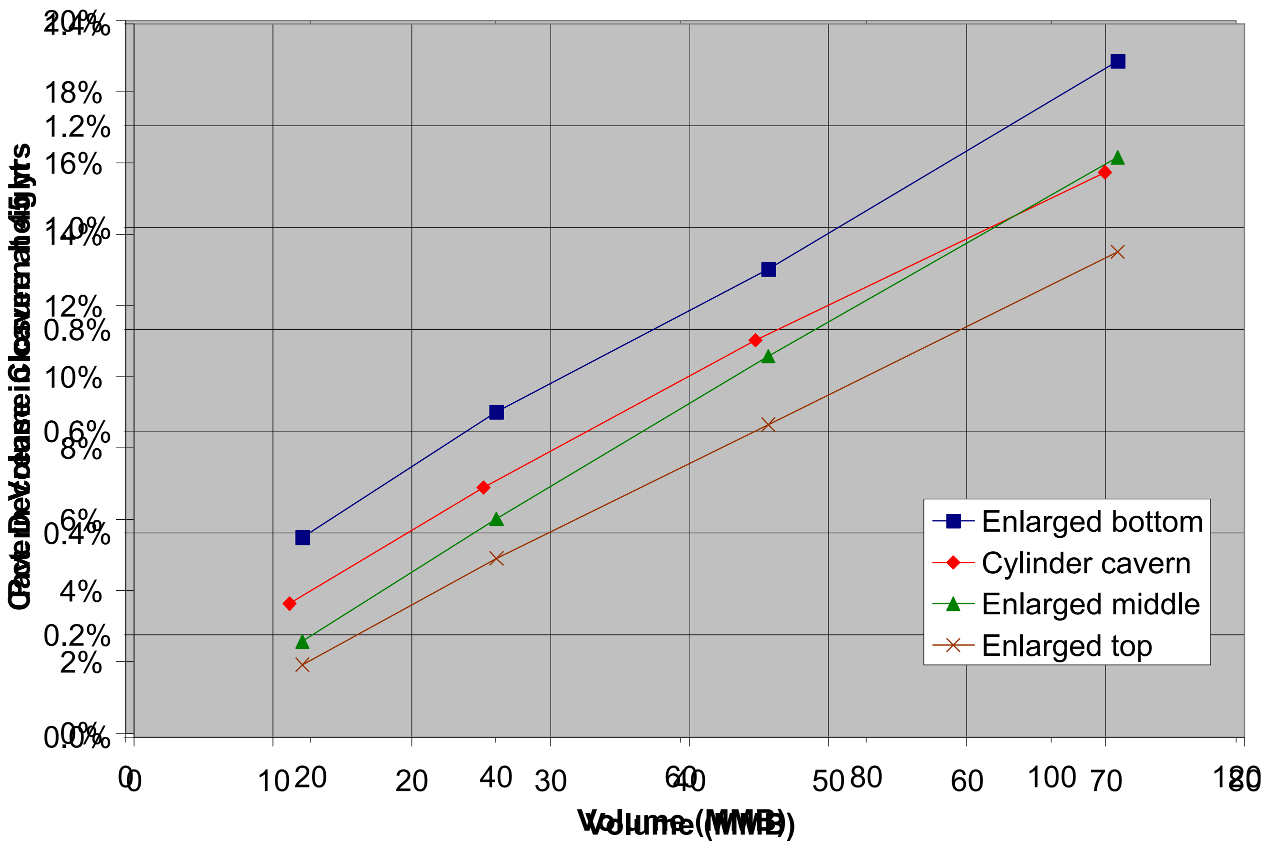
Cavern Volume Closure, Decrease in Cavern Height



Rank order (Best to Worst):

1) Enlarged top
2) Enlarged middle
3) (tie) Cylinder
4) Enlarged bottom

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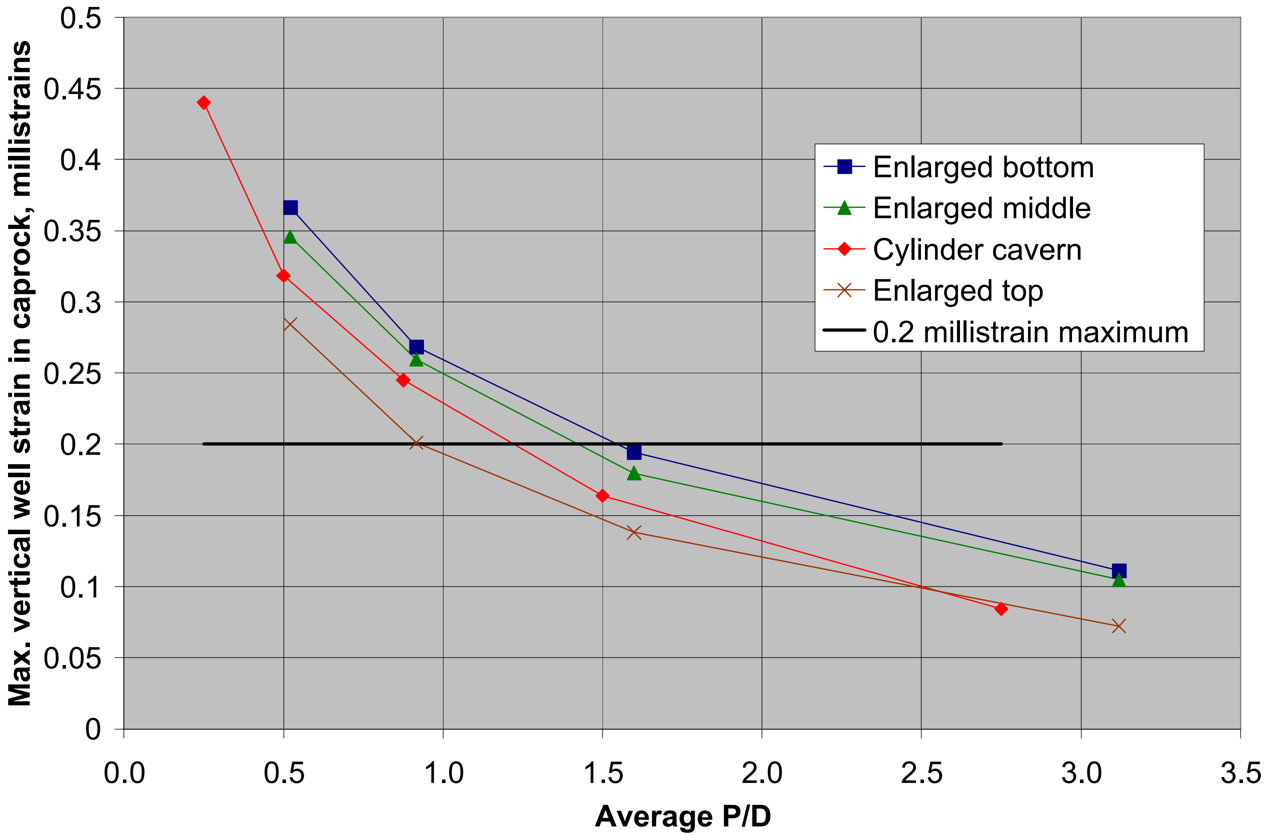
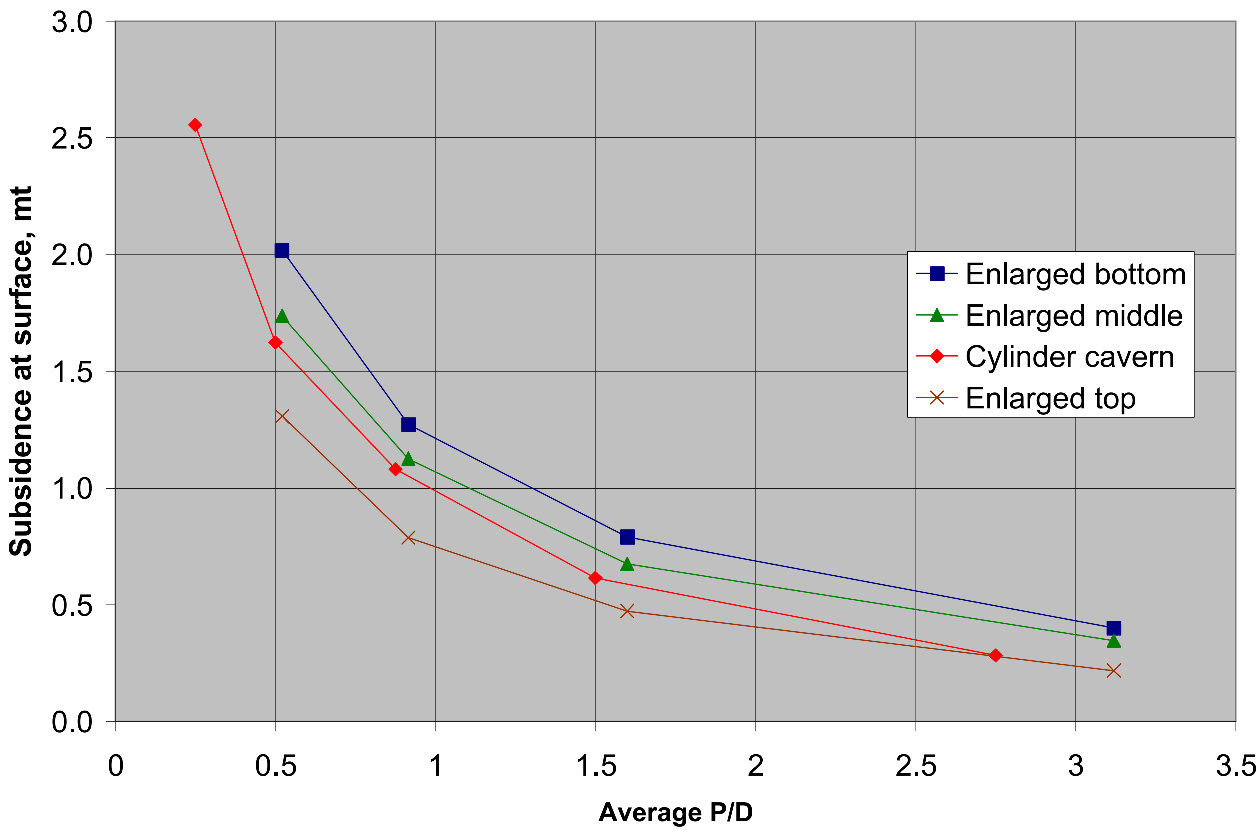
Axial Well Strain in Caprock



Rank order (Best to Worst):

1) Enlarged top
2) Cylinder
3) Enlarged middle
4) Enlarged bottom

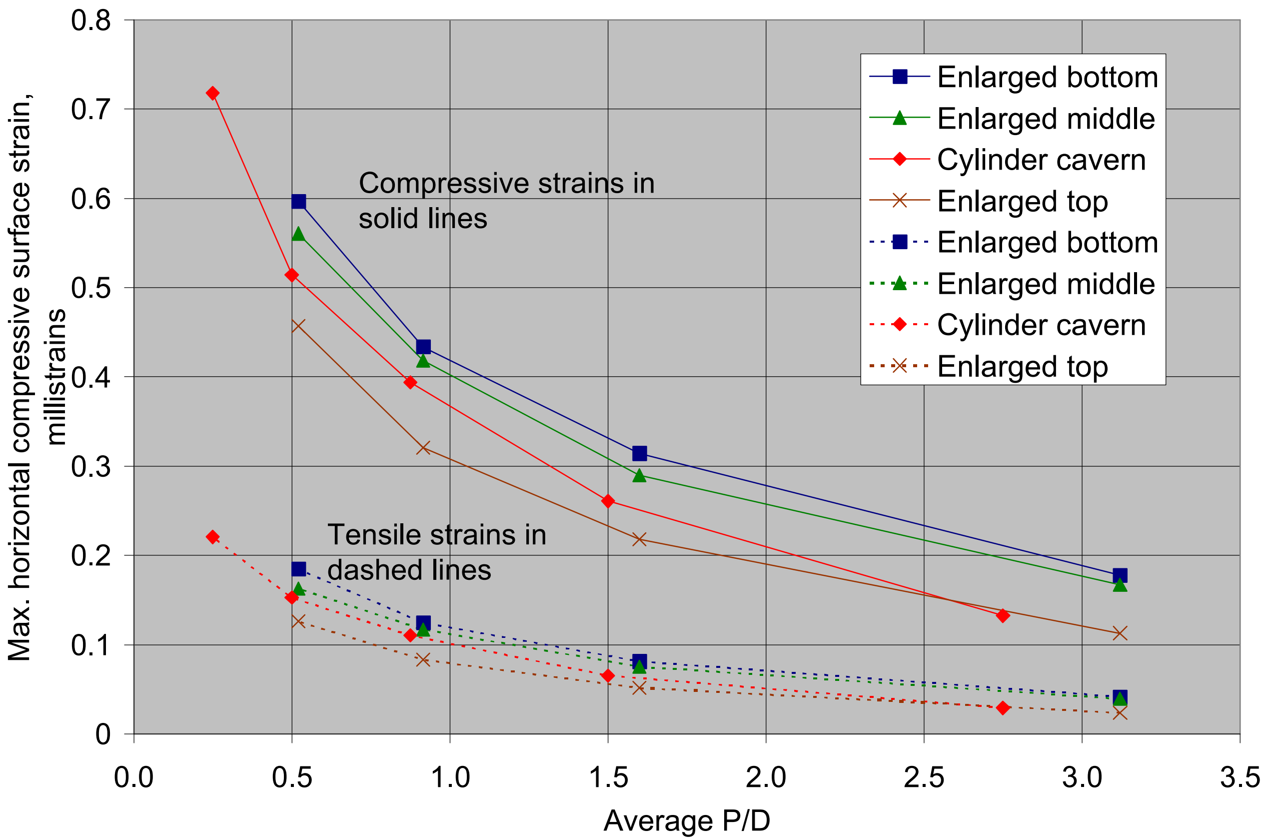
Surface Subsidence



Rank order (Best to Worst):

1) Enlarged top
2) Cylinder
3) Enlarged middle
4) Enlarged bottom

Potential Strain to Surface Structures



Maximum allowable strain for surface facilities is 1 millistrain for both compression and tension.

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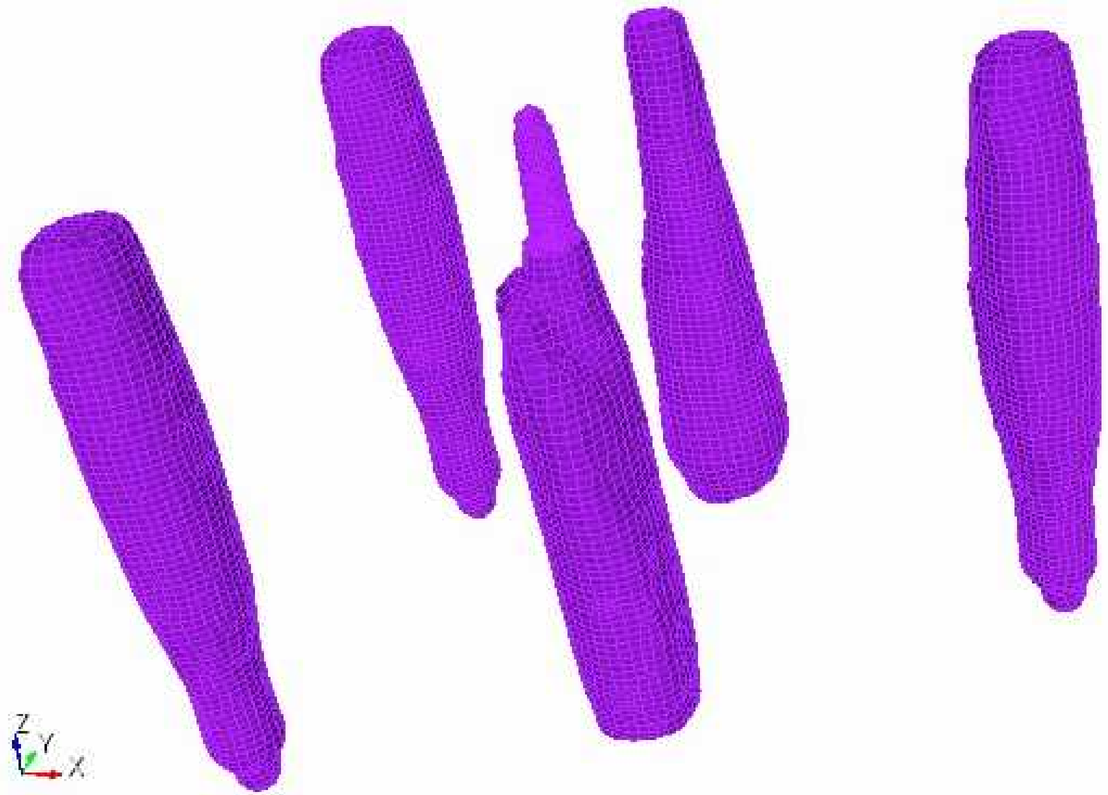
Summary of Cavern Shape Rankings

Design Factor	1st	2nd	3rd	4th
Safety factor in salt	enlarged middle	cylinder	enlarged bottom	enlarged top
Cavern volume closure	enlarged top	enlarged middle, cylinder		enlarged bottom
Axial well strain in caprock	enlarged top	cylinder	enlarged middle	enlarged bottom
Surface subsidence	enlarged top	cylinder	enlarged middle	enlarged bottom

Sonar-based Cavern Geometries



- Improved capabilities to mesh actual caverns
- Small-scale deformities may be more likely locations for dilatant damage

Conclusions

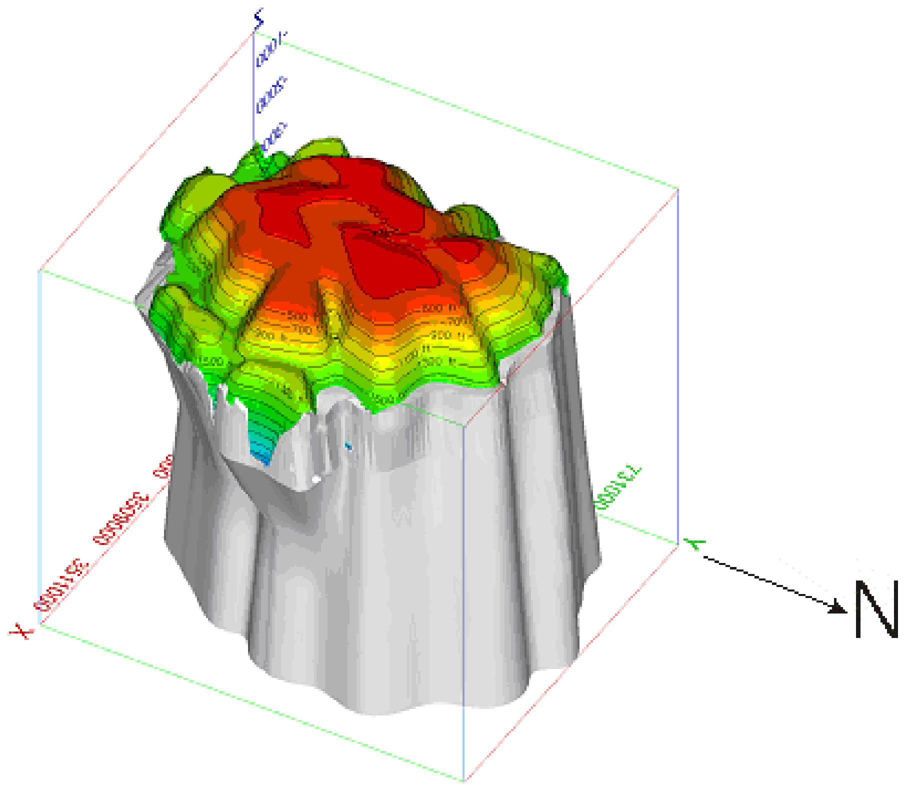
- The enlarged top caverns had the best performance when evaluated against the design factor of cavern volume closure, axial well strain in the caprock, and surface subsidence. This performance comes at the expense of the greater possibility for dilatant or shear damage, for which the enlarged top caverns performed the worst.
- The enlarged middle design has the highest safety factors of the four designs; existing cylindrical caverns could be preferentially leached with enlarged middles and maintain safety factor.
- The enlarged bottom caverns had generally the worst performance of the four designs.
- The analyses provide evidence that the mandatory minimum P/D ratio of 1.78 should be re-examined.

Future Analyses

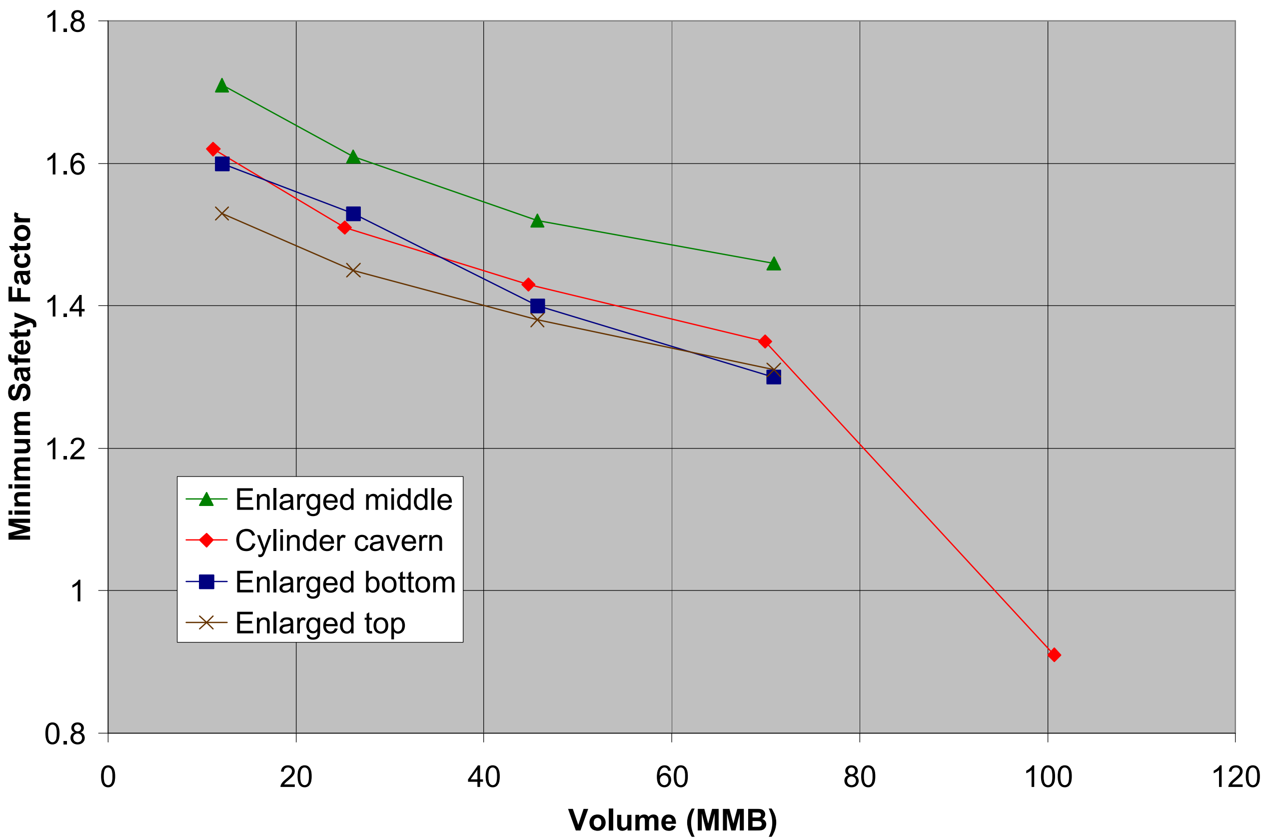
- Evaluate axial well strains in salt, compare to strains in caprock
- Add steel casings and cement liners to computational mesh to evaluate stress/strain on liners, surrounding salt.
- Model salt dome with surrounding sandstone/caprock.
- Use different site as a model (e.g., Bayou Choctaw), including different stratigraphy, harder salt properties.
- Evaluate pressures at the casing seat; include casing seat/roof geometries for optimum shape and location.

Extra Slides

Perspective view of salt dome and caprock (Rautman, 2005)



Min. Safety Factor vs. Volume (MMB)



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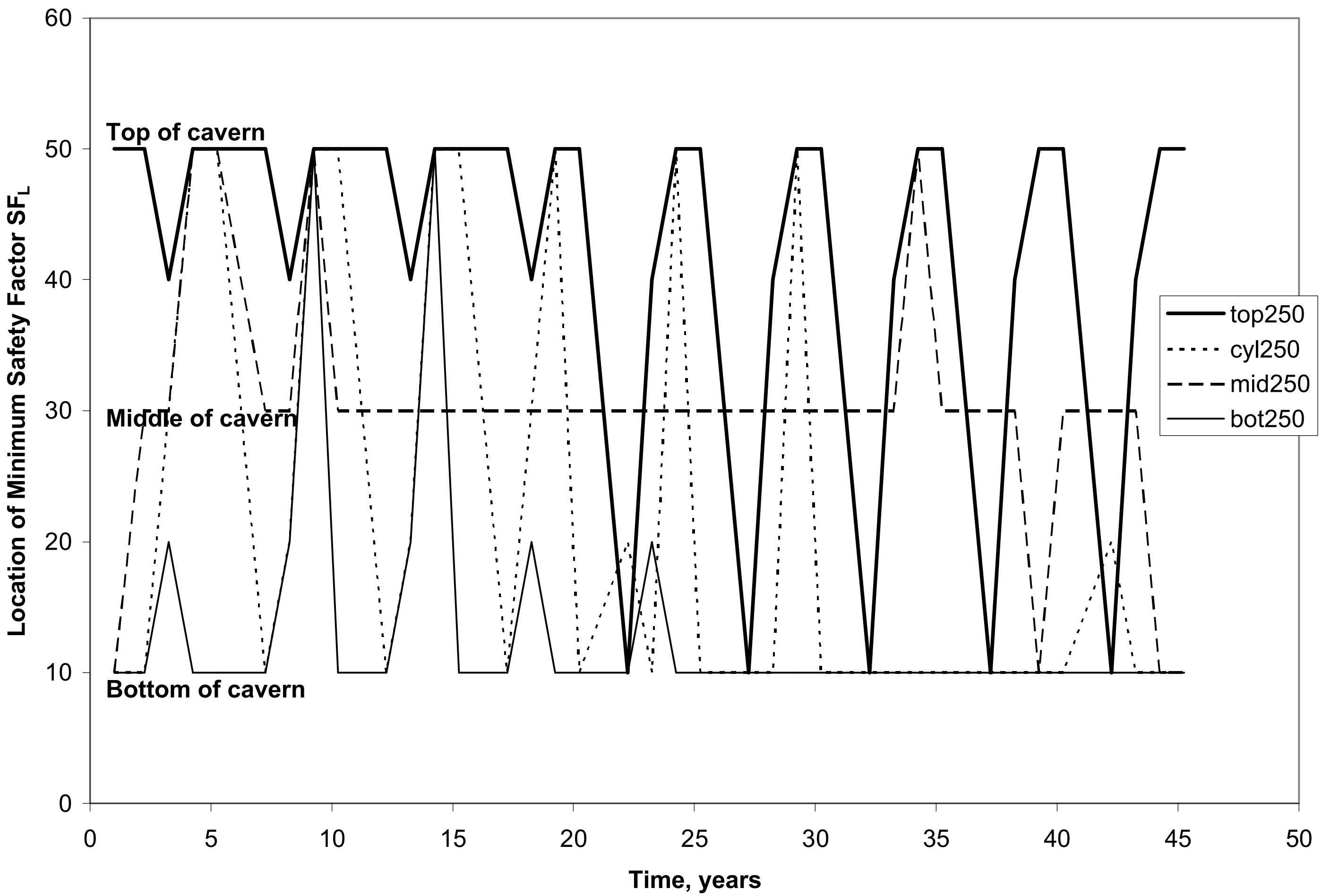
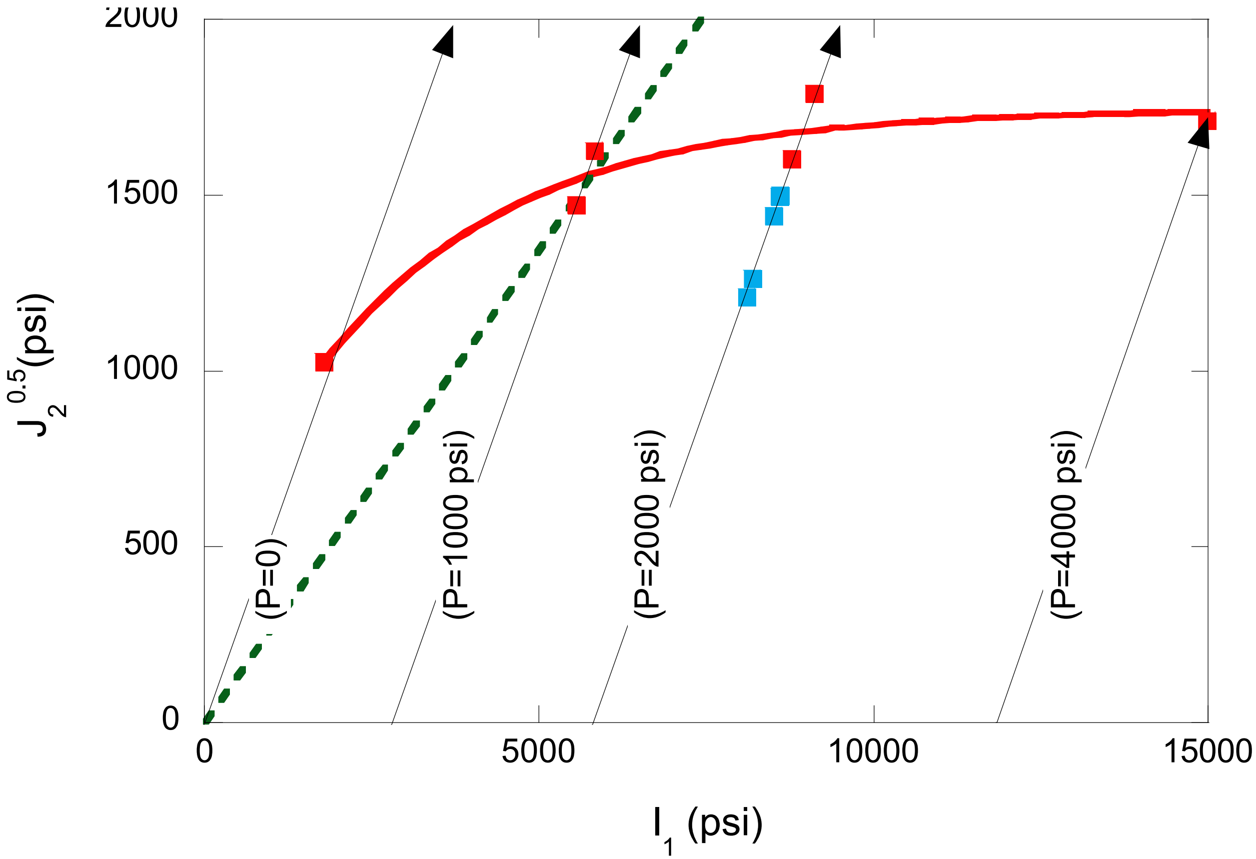
Location of Minimum safety Factor (max deviatoric stress)



Dilation criterion (red line) and data of Big Hill salt compared to typical salt (green line) from Lee et al., 2004 (blue data points from Ehgartner et al. 2002).



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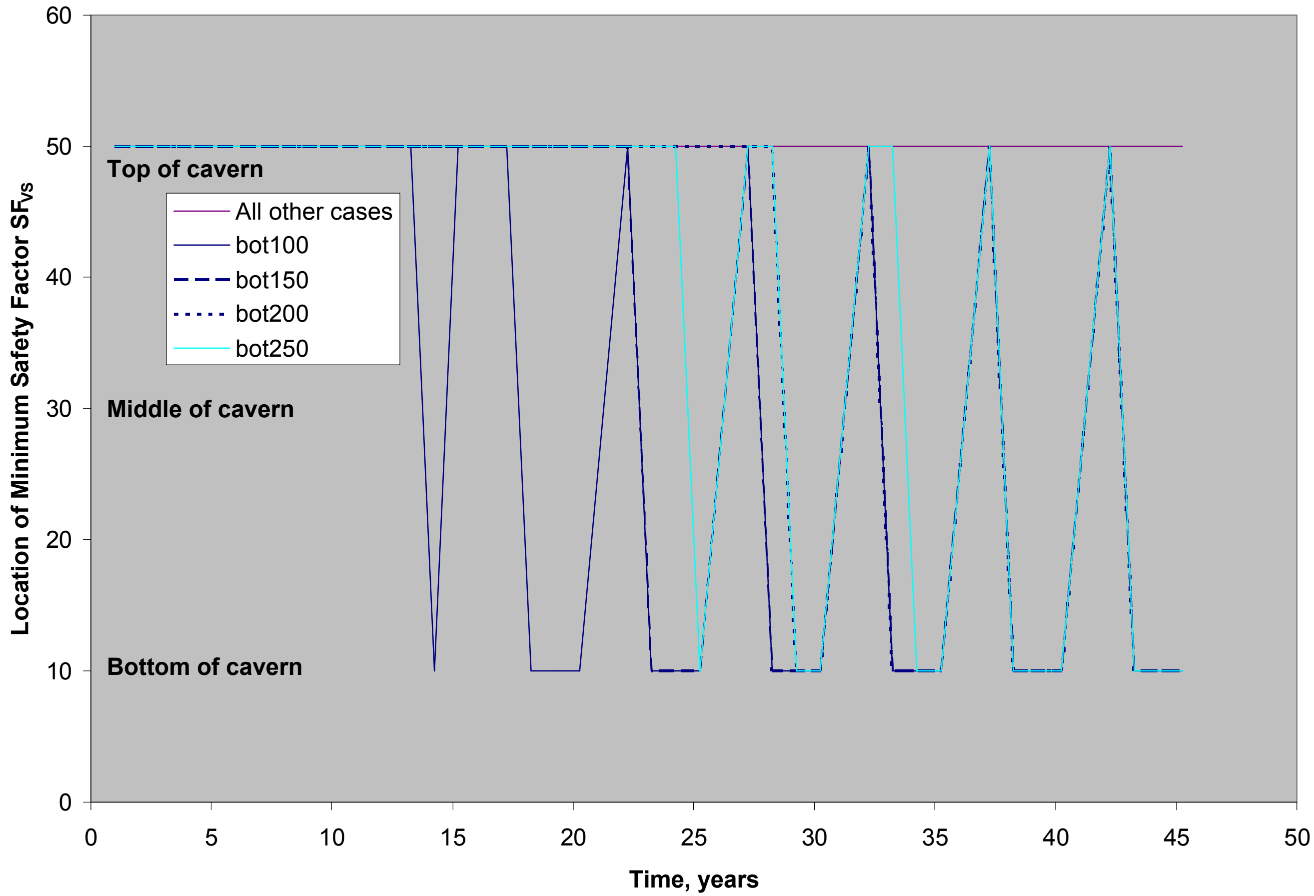
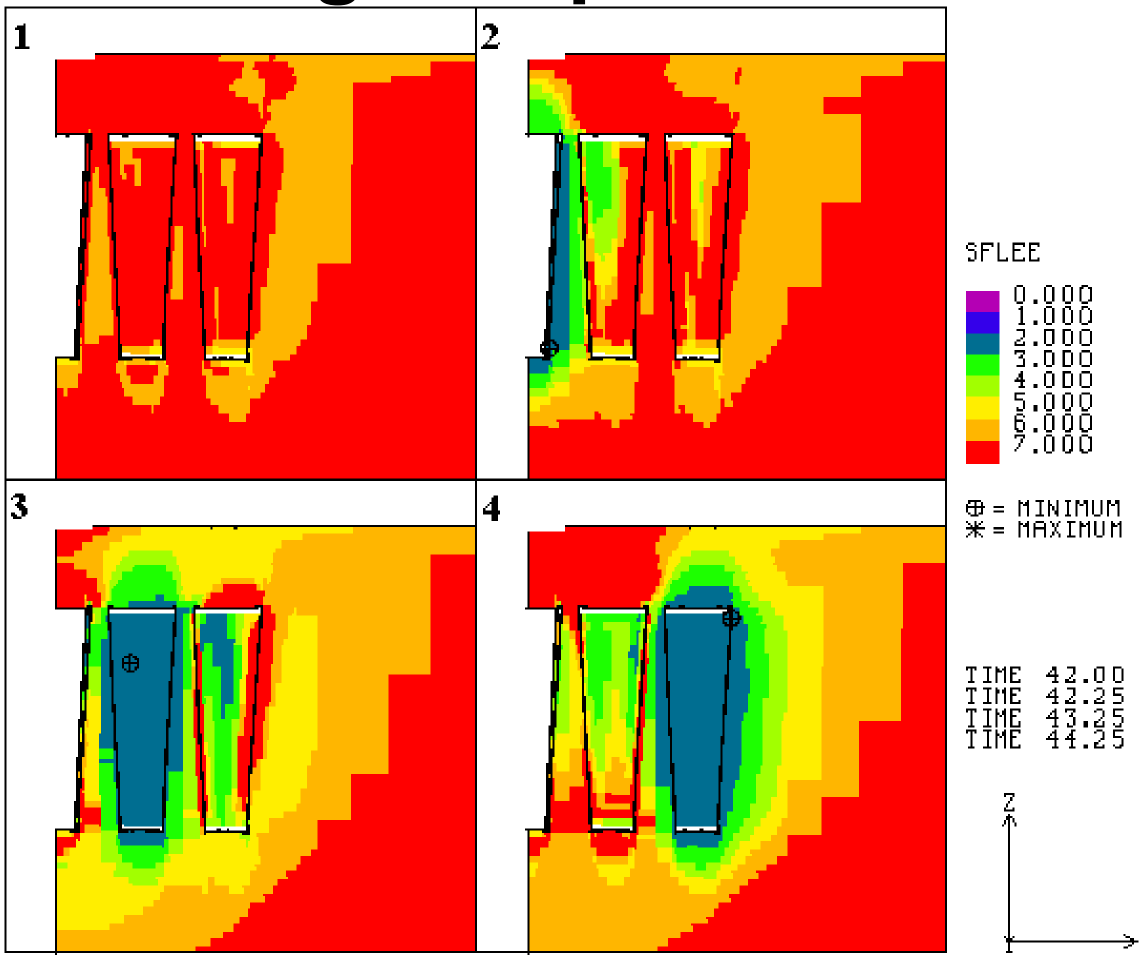
Location of minimum Van Sambeek safety factor during workover cycles



Contour plot of Lee safety factor, enlarged top caverns



Lee Safety Factor, Time in Years
Frame 1: Operating Pressure Frame 2: Well 1 Workover
Frame 3: Well 2 Workover Frame 4: Well 3 Workover

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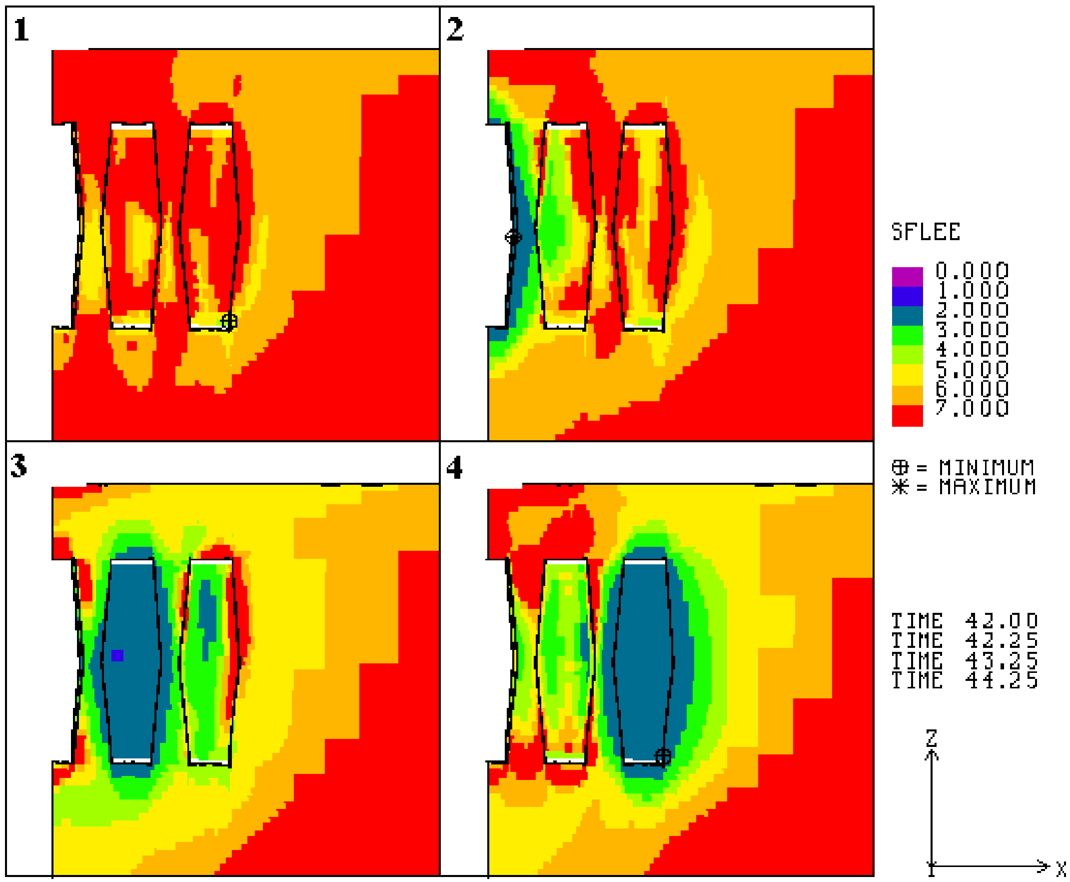
Contour plot of Lee safety factor, enlarged middle caverns



Lee Safety Factor, Time in Years
Frame 1: Operating Pressure Frame 2: Well 1 Workover
Frame 3: Well 2 Workover Frame 4: Well 3 Workover

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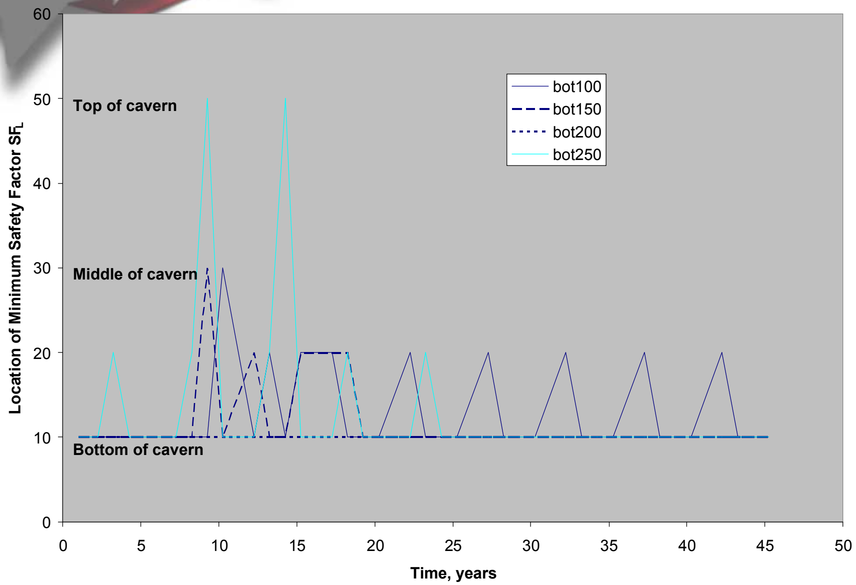
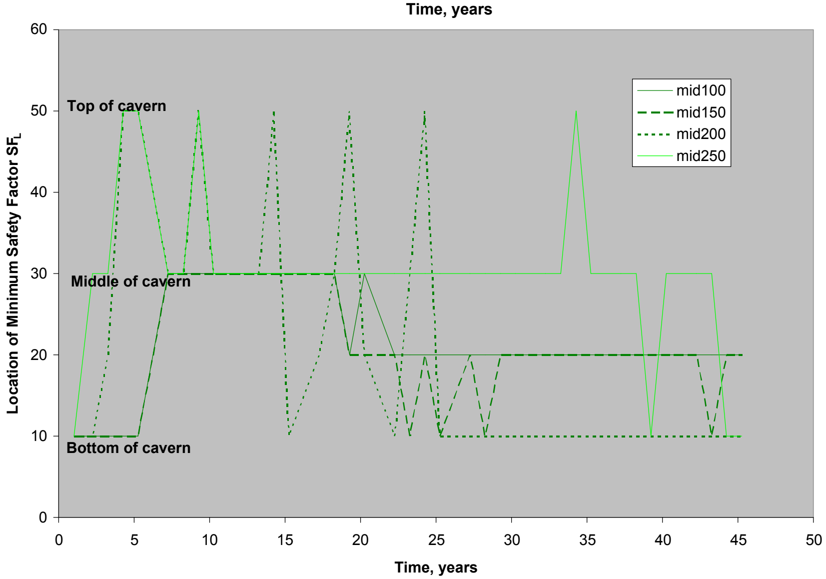
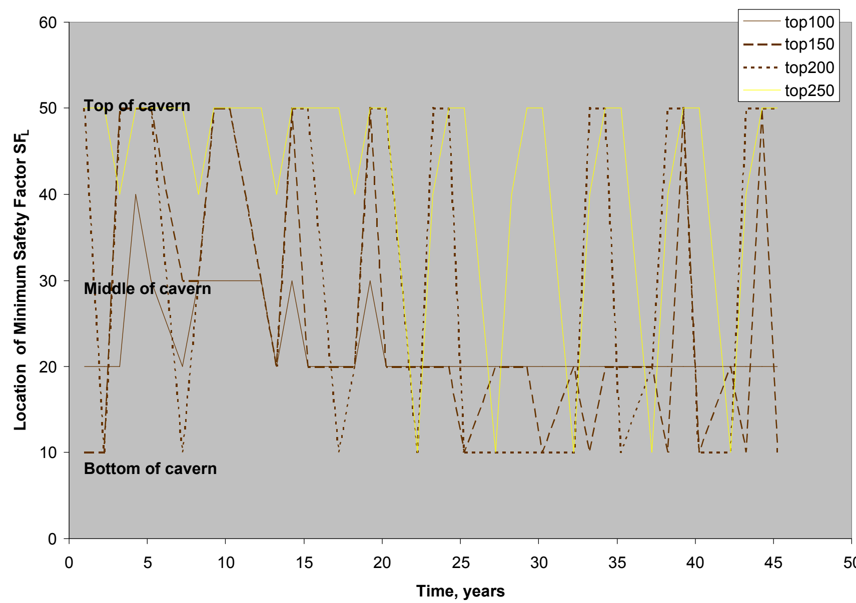

Top of cavern
Middle of cavern
Bottom of cavern
bot100
bot150
bot200
bot250
Location of Minimum Safety Factor SF_L
Time, years


Top of cavern
Middle of cavern
Bottom of cavern
mid100
mid150
mid200
mid250
Location of Minimum Safety Factor SF_L
Time, years


Top of cavern
Middle of cavern
Bottom of cavern
top100
top150
top200
top250
Location of Minimum Safety Factor SF_L
Time, years

Contour plots of vertical displacement (displacements in meters)

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The quantity "P/D ratio" is defined in the Level III Design Criteria for the SPR (DOE, 2001). "Pillar" refers to the minimum thickness of the web of salt remaining between any two adjacent caverns, or between the cavern and salt dome perimeter. "Diameter" refers to the average cavern diameter. To ensure cavern structural integrity, the Level III criteria mandate that the P/D ratio for each cavern must remain greater than 1.78 after five complete drawdown cycles. Typically in the field, cavern shapes are not uniformly sized, spaced, and shaped cylinders, and the definition of the Level III P/D ratio is perhaps inadequate. Two alternate definitions for the P/D ratio for non-constant cavern diameters are introduced in this report. The minimum P/D ratio is calculated at the point of minimum pillar thickness, i.e., minimum pillar thickness/ maximum cavern diameter. The average P/D ratio is obtained by integrating the P/D at every elevation along the height of the caverns and dividing by the height. For the cases simulated in this report, the cavern diameter is a known linear function of height, and an average P/D ratio may be derived. For example, for the radius of the enlarged top (or bottom) cavern *r*, radius of the smaller end *r0*, a 100-ft difference between smaller and larger radii, a 750-ft center-to-center cavern spacing, and normalized height of the cavern *x*, *x*={0,1}, the following expression is obtained for the average P/D:

$$r = r_0 + 100x;$$

$$\frac{P}{D} = \frac{\text{(center} - \text{to} - \text{center distance between caverns) - (cavern diameter)}}{\text{cavern diameter}}$$

$$= \frac{750 - 2r}{2r} = \frac{750}{2r_0 + 200x} - 1;$$

$$\left(\frac{P}{D}\right)_{avg} = \frac{\int \frac{P}{D} dx}{x(=1)} = \int_0^1 \frac{750}{2r_0 + 200x} dx - \int_0^1 dx = \frac{750}{200}\left(\ln \frac{200 + 2r_0}{2r_0}\right) - 1.$$