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CAVITY SHAPE CHARACTERIZATION OF A RUBBLE-FILLED, SOLUTION-MINED CAVITY

Max Ramey

Agapito Associates, Inc., Grand Junction, Colorado, USA

Jozef Descour

C-Thru Ground, Inc., Littleton, Colorado, USA

Michael Hardy

Agapito Associates, Inc., Grand Junction, Colorado, USA

Abstract

To comply with permit conditions and to provide valuable data for locating future wells, American Soda, L.L.P. (ASLLP) needed to characterize the shape of cavities developed by solution mining nahcolite. The ASLLP cavities were difficult to characterize because solution mining removed less than 25% of the cavity volume leaving the cavern filled with rubblized insolubles. After evaluating several methods, a novel downhole, seismic technique and partial fluid displacement were selected for demonstration. In early 2004, ASLLP performed a downhole seismic reflector tracing and partial fluid displacement to characterize the shape of a mature cavity. The cavity was initially estimated to be on average 95.5 ft in radius and 492 ft in height. The upper cavern volume estimated from the downhole seismic reflector tracing and the partial fluid displacement method agreed within 10%. The overall cavity shape and volume determined by the downhole seismic method compared favorably with volume estimated from the historical nahcolite production. The shape characterization indicated that the maximum cavity radius was 58% larger than the average radius.

Introduction

As a condition of the Environmental Protection Agency (EPA), Bureau of Land Management (BLM) and Colorado Division of Mining and Geology permits, ASLLP was required to evaluate cavity shape characterization techniques and perform a cavity shape characterization if technically and economically feasible. Shape characterization techniques are well advanced for solution-mined caverns in salt where the mined cavern is open and sonar surveys through clear liquor can be performed. At ASLLP, solution mining removes only 20% to 25% of the host rock leaving a porous, rubblized, insoluble residual in the cavity. Sonar surveys cannot penetrate this residual material. After reviewing all alternative methods of shape characterization, two methods were selected for demonstration. In June 2004, ASLLP submitted "American Soda Cavity Characterization of Well 28-21, American Soda Piceance Creek Mine" to each of the above agencies. This paper presents the results of the cavity shape demonstration.

The ASLLP solution mining method consists of single, vertical wells solution mining nahcolite from a 500 ft mineralized thickness of 20% to 24% nahcolite ($NaHCO_3$) and 76% to 80% oil shale. The top of the nahcolite mineralization is at a depth of approximately 1,600 ft from surface. The method uses high-temperature water to thermomechanically fracture the nahcolitic oil shale and dissolves the nahcolite into a solution. A nitrogen gas cap is maintained on the top of the solution mining cavity to limit vertical growth. Upon completion of solution mining, the solution mining cavity is essentially filled with the residual, rubblized oil shale which constitutes 76% to 80% of the original mass of the rock within the cavity. Further details of the ASLLP project are presented in Ramey and Hardy (2004).

Several cavity characterization methods were evaluated including

- fluid displacement
- gravity measurements
- magneto-tellurics
- surface seismic profiling
- three-dimensional seismic imaging
- micro-seismic imaging
- well-to-well (cross-hole) seismic imaging
- downhole seismic reflector tracing

A combination of two cavity characterization methods was chosen (American Soda 2004). The first used a single well downhole seismic reflector tracing (TRT™) method. The second method selected was partial fluid displacement. This method was selected to verify the downhole seismic results in the upper portion of the solution mining cavity. The downhole seismic method selected for this application was novel and untried in elevated-temperature, rubble-filled cavities. The method involved using small conventional explosive charges as the seismic source. The downhole seismic method was designed to produce images of the average cavity perimeter as defined by seismic energy reflected from the cavity boundaries. The method was expected to provide good resolution of the edges of the upper half of the solution mining cavity, whereas lower resolution was expected for the lower half of the cavity due to the relative positioning of the sources and receivers, and the reflected seismic signal strength.

The seismic data were recorded and processed by NSA Geotechnical Services, Inc., using proprietary software TRT™ (technology presently owned and operated by C-Thru Ground, Inc).

TRT™ Background

TRT™ uses seismic waves to identify structures within the rock mass that reflect seismic waves (Neil et al. 2001). The technique is based on acoustic impedance contrasts (the product of density and seismic velocity) that occur at boundaries between geological layers or discontinuities. These discontinuities act as mirrors, returning part of the seismic energy to a detector. This energy is then analyzed to determine the location and nature of the reflecting boundary. A transition from a material with lower acoustic impedance to one with a higher value results in a positive reflection coefficient, and vice versa. Features such as fractured zones within a more solid rock mass will also give rise to reflections. The larger the acoustic impedance contrast, the larger the reflection coefficient and the easier it is to detect the echo.

A typical TRT™ survey uses an array of ten sensors (receivers) and a comparable number of seismic sources (blasts or hammer blows) initiated at different locations. For each source, a seismograph records a data file that contains seismic signals received at each sensor. The seismic signals are inspected to measure the travel times of P- and/or S-waves between sources and sensors that determine the seismic velocity of each wave type in the rock mass. Typically, these velocity values are used to define the velocity model within a three-dimensional orthogonal block selected for seismic data processing. The volume of the block is subdivided into elementary cubes (voxels) by a uniform grid. The spacing of the grid defines resolution of the ground image to be reconstructed by the TRT™.

The velocity model is used by TRT™ to calculate the times required for a signal to travel from each source to each individual node of the grid and back to each receiver. Subsequently, for each node, the parts of all recorded seismic signals matching the appropriate travel times are added together. For actual reflective structures, such as cavities, faults, etc., the signals should superimpose, resulting in a large positive or negative value (reflector magnitude). If no structure is present at the node, the signals should effectively cancel, resulting in near-zero values. Contour plots of a specific reflector magnitude (positive and negative) are made throughout the survey block to isolate and identify amplitude anomalies that possibly represent reflections from actual structures in the rock mass.

In practice, several factors must be considered in solving a particular problem. For example, there is a trade-off between the levels of detail obtained in the images versus the distance that can be imaged. Large distances require a large grid spacing that limits the frequency range of seismic signals acceptable for data processing and results in a relatively low level of detail. Also, several filters are often employed to modify the raw seismic signals to subdue noise and enhance features in a particular area of interest.

Downhole Seismic Method

The ASLLP well completion consisted of two 7-inch casings grouted side-by-side within a 19-inch borehole to a depth of 1,680 ft, which corresponds with the top of the solution mining cavity. A 4½-inch tubing was installed within each 7-inch casing. The end of the short 4½-inch tubing was positioned at a depth of 1,758 ft, 78 ft into the top of the solution mining cavity. The end of the long 4½-inch tubing was positioned at a depth of 2,172 ft, at the base of the solution mining cavity. The solution mining occurred over an interval of 492 ft (Figure 1).

The downhole seismic method consisted of positioning an array of ten specially manufactured, high-tempera-ture hydrophones within the short 4½-inch tubing of the well and initiating downhole source charges at specific elevations within the long 4½-inch tubing.

A string of ten hydrophones at 20-ft centers was used as the receivers. The receivers were attached to a multi-wire cable and lowered to the desired depth in the 4½-inch short tubing. The depth was precisely measured by performing a gamma log into the adjacent 4½-inch-long tubing and locating a short half-life radioactive source attached to the bottom end of the hydrophone cable. The surface end of the hydrophone cable was connected to the seismograph for digital recording of detected seismic signals.
A multi-barrel, borehole gun operated by WellServ (Weatherford) was used as the seismic source. The source was lowered to the desired depth in the injection pipe and then fired to generate seismic waves. The charge for each barrel was adjusted to prevent overloading/saturation of the

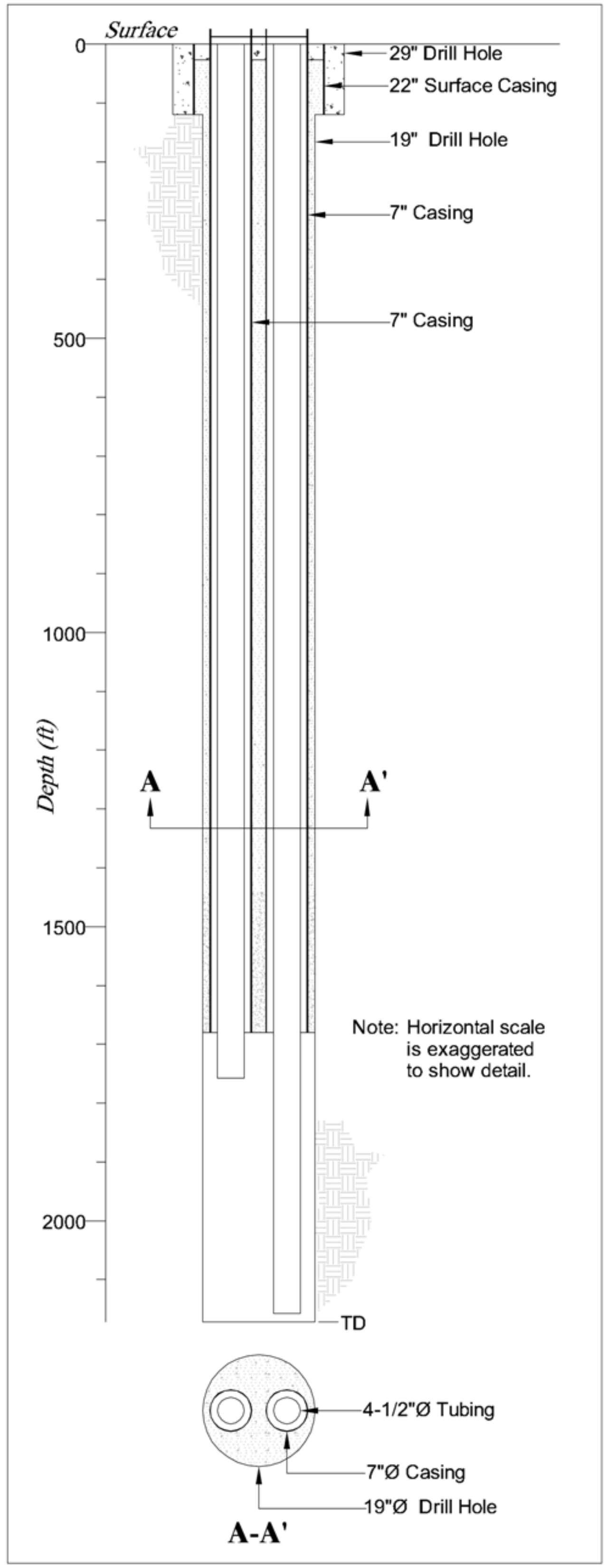

Figure 1. ASLLP Well Completion

hydrophones by seismic signals generated by each shot.

Solution mining was suspended during the time of the survey. The nitrogen gas cap was released from the well and replaced with saturated sodium chloride (NaCl) brine. The brine in both tubings provided seismic coupling through the pipe walls to the brine and the rock mass outside for both the seismic sources and the receivers. A bridge plug was set within the 4½-inch short tubing to simplify lowering the hydrophones into the tubing and to protect the hydrophones from high-temperature fluid.

The survey was conducted using three positions of hydrophones and sources (Figure 2):

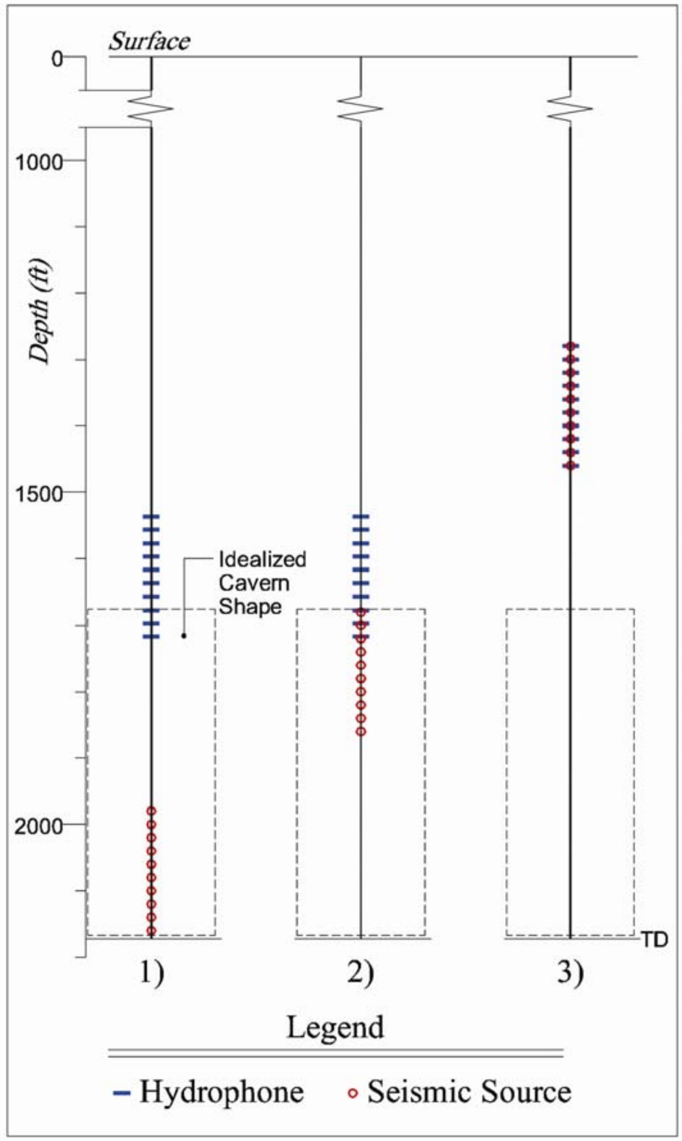

Figure 2. Positions of Hydrophones and Sources

1. In the first set, the hydrophones were at the bottom of the short tubing at a depth ranging from 1,717 ft to 1,537 ft below the local ground elevation. The sources were fired in ten locations at 20-ft intervals up the long tubing starting at 2,160 ft and ending at 1,980 ft. This configuration targeted mainly the inner boundaries of the extraction zone with emphasis on horizontal extent of structural changes. Note that the depth of the short tubing was approximately 1,728 ft. Only three out of ten hydrophones, therefore, were inside the solution-mined cavity.

2. In the second set, the hydrophones remained unchanged, and the sources were fired in 20-ft intervals over a depth range from 1,860 ft to 1,680 ft. This configuration of sources and receivers targeted the upper part of the extraction zone and the vertical features below the line of sources.

3. For the third set, the hydrophones were moved to a depth range from 1,280 ft to 1,460 ft, and the sources were fired in 20-ft intervals over a depth range from

1,280 ft to 1,460 ft. This configuration of sources and receivers was located entirely above the solution-mined cavity and was intended mainly to target the top of the cavity.

Seismic Data Analysis

The goal of directly recording the actual shot time for each source (time break) was not accomplished as originally planned. However, analysis of the seismic records has shown that the injection and production steel pipes combined provided a very reliable waveguide. This waveguide carried seismic energy from each shot in the injection hole with nearly a constant velocity of 16,700 ft/s, both up and down both pipes (Figure 3). This velocity was higher than the velocity of seismic waves in the surrounding ground. The velocity measurement was confirmed by sledge hammer strikes at the ground surface near the surveyed well that were recorded by hydrophones in the production hole at depths ranging from 1,537 ft to 1,717 ft below the surface.

The stable velocity of seismic signals traveling along the pipes was used to calculate the source time for each shot location. Each record was then shifted back so the source time was at the origin of that record. Thus, all records were made compatible with respect to the timing of their sources.

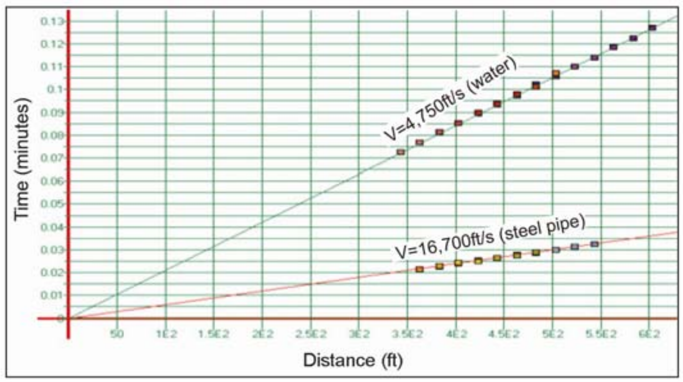

Figure 3. Seismic Energy Velocities

The seismic records were dominated by waves traveling along the steel pipes (velocity 16,700 ft/s) and the tube waves in water (velocity 4,750 ft/s), as shown in Figure 4. No seismic velocity numbers measured in the ground were available for the site. Therefore, the average velocity values for the mine zone were derived from Young's Modulus = 1,402,000 psi and Poisson's Ratio = 0.41, which were provided by Agapito Associates, Inc. (AAI). The resulting velocity numbers of 10,500 ft/s for P-waves and 4,100 ft/s for S-waves were used to generate two average- velocity models within the orthogonal block selected for seismic data processing. The square base of the block was 400 ft by 400 ft, and the vertical dimension was

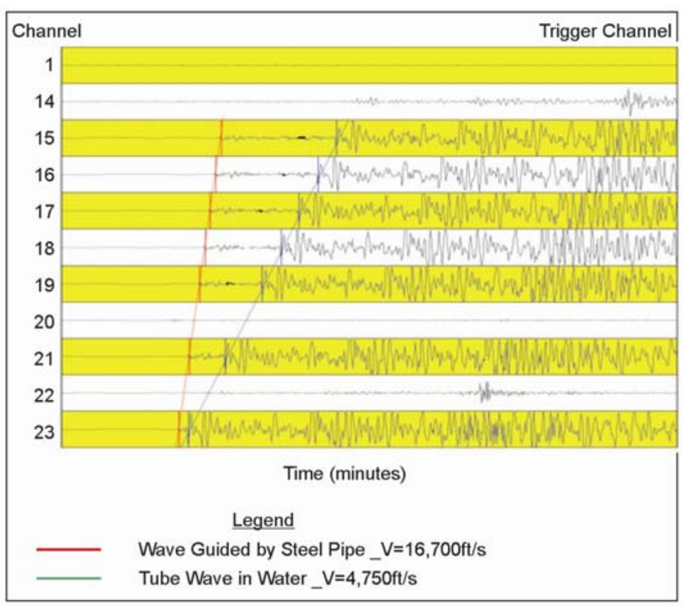

Figure 4. Example Seismic Record

set in the depth range from 2,190 ft to 1,240 ft. The block was centered with respect to the well.

Seismic data for each set of sources and receivers were processed separately, once for S-wave reflections using an S-wave velocity model and once for P-wave reflections using a P-wave velocity model. The results for all three sets and for both wave modes were normalized and merged together to produce the final image of the surveyed site.

Seismic Data Interpretation

Figure 5 shows the tomographic slice through the merged image and the contour anomalies in the parallel projection. Figure 6 shows the contour images alone. The dark blue colors typically delineate weaker/fractured zones or open caverns. The depths of these anomalies in the two images correspond well with high-grade nahcolite zones. This correlation adds to the credibility of the imaged horizontal extent of possible solution caverns. The dark blue 'profile' marked with dashed a red line around the anomalies could be indicative of an edge of the solution-mined cavity.

From the graphical representation of the low-velocity zones, an average radius of the cavity at various elevations was developed and is shown in Table 1 and Figure 7.

The cavity was initially estimated to be on average 95.5 ft in radius and 492 ft in height. This radius was calculated from the total tons of nahcolite dissolved in the cavity, 132,736, of which 120,014 tons were produced and 12,722 tons remained in solution left within the cavity. This radius and the associated cavity volume could be compared to the volume interpreted from the seismic model. The seismic model predicts a volume 6% higher in tons dissolved than the historical production.

The volume of the seismic model is very sensitive to the following:

- Actual percent of nahcolite of the individual zone
- Symmetry of the solution-mined cavity
- Accuracy of the interpreted cavity radius
- Percentage of nahcolite that was dissolved within the cavity

Partial Fluid Displacement Method

The partial fluid displacement method consisted of injecting nitrogen gas into the top of the solution mining cavity, then recovering the displaced solution from the bottom of the cavity. From the volume of displaced fluid and the assumed porosity of the rubble remaining in the cavern, the effective cavity radius of the upper portion of the cavity could be calculated. This radius and the associated cavity volume could be compared to the values determined from the seismic model as a comparison of methods. The displacement was intended as a secondary method to verify the finding of the seismic method.

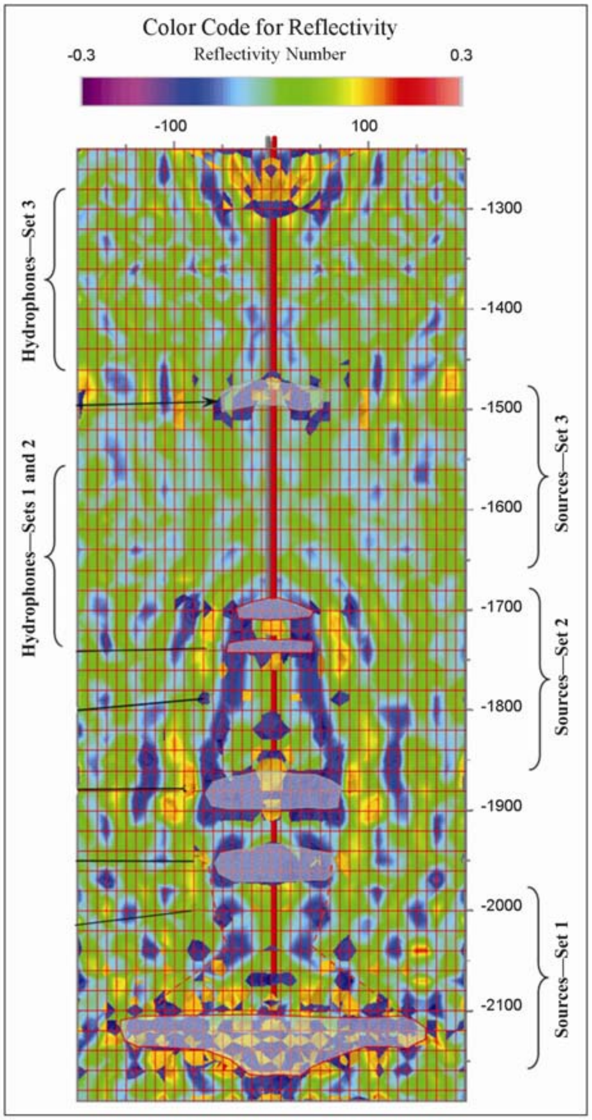

Figure 5. Tomographic Slice through Merged Image and Contour Anomalies

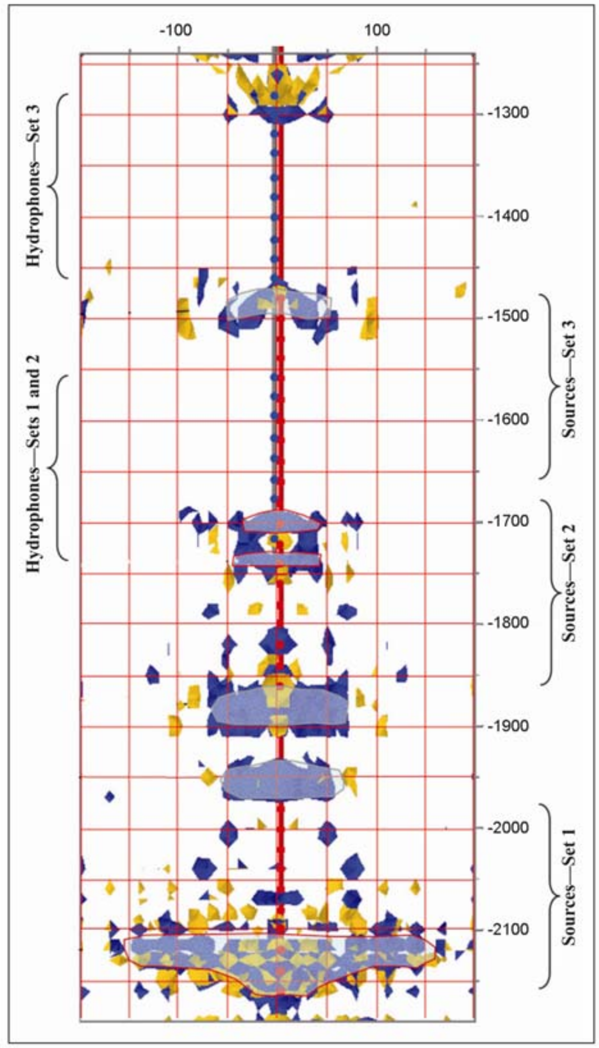

Figure 6. Contour Anomalies

Upon completion of the downhole seismic method, the partial displace-ment of the liquor in the cavern with nitrogen gas in the upper portion of the solution-mining cavity was initiated. A partial displacement was chosen due to the volume of nitrogen gas required for the displacement and the cost of the nitrogen gas.

The gas/fluid interface was measured by stopping the displace-ment, flushing the long 4½-inch tube with ambient-temperature fluid, and performing successive temperature logs to identify a temperature gradient anomaly. In both gas/fluid interface measurements, a distinc-tive temperature gradient anomaly was observed. The center of the anomaly was chosen as the gas/fluid interface.

Table 1. ASLLP Well Interpretive Radii and Tonnage from Seismic Model

Depth (ft)	Adjacent Core Well (% Nahcolite)	Radius (ft)	$NaHCO_3$ (Tons)
1,680	—	0	0
1,700	27%	20	448
1,720	13%	41	871
1,740	26%	42	1,902
1,760	27%	47	2,473
1,780	23%	50	2,384
1,800	30%	52	3,364
1,820	25%	56	3,251
1,840	15%	62	2,391
1,860	8%	67	1,396
1,880	8%	69	1,481
1,900	20%	71	4,181
1,920	13%	70	2,642
1,940	17%	65	2,979
1,960	14%	61	2,083
1,980	5%	60	746
2,000	0%	56	0
2,020	15%	56	1,951
2,040	25%	59	3,609
2,060	18%	65	3,066
2,080	43%	85	12,734
2,100	41%	120	24,483
2,120	40%	151	37,821
2,140	24%	151	22,693
2,160	9%	60	1,344
2,180	20%	25	518
Averages	20%	66.4	
Sum			140,811

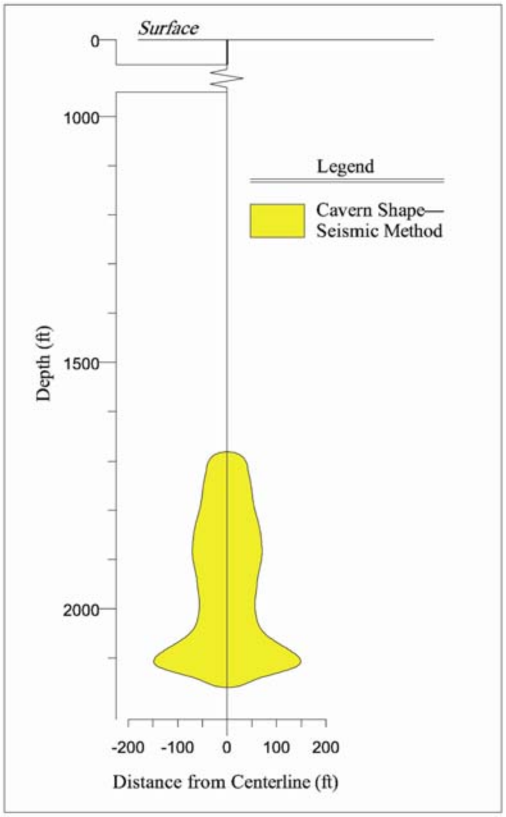

Figure 7. Average Cavity Radius versus Depth

After 11 days of displacing the fluid from the cavity, the gas/fluid interface was moved 39 ft into the cavity and displaced 121,262 gallons of fluid. After 16 days of displacing the fluid, the gas/fluid interface was moved 44 ft into the cavity. A total of 212,572 gallons of fluid were displaced.

The displacement model is sensitive to the following:

- The percent of residual fluid retained during the displacement process
- The accuracy of the gas/fluid interface measurement
- Assumed void distribution in the volume displaced (assumed equal to the nahcolite volume removed with no slumping or compaction)

Comparison of Seismic and Displacement Methods

The comparison of the results of the displacement method data to the seismic method data is shown in Table 2 and the detail of Figure 8.

Table 2. Comparison of Displacement Method versus the Seismic Method

Interface Depth (ft)	Displacement Method (ft^3)	Seismic Method (ft^3)	Percent Difference	Displacement Method Radius (ft)	Seismic Method Radius (ft)
1,680	0	0	0%	0.0	0.0
1,719	80,334	89,237	11.10%	25.6	30.5
1,724	138,627	125,617	-9.40%	60.9	42

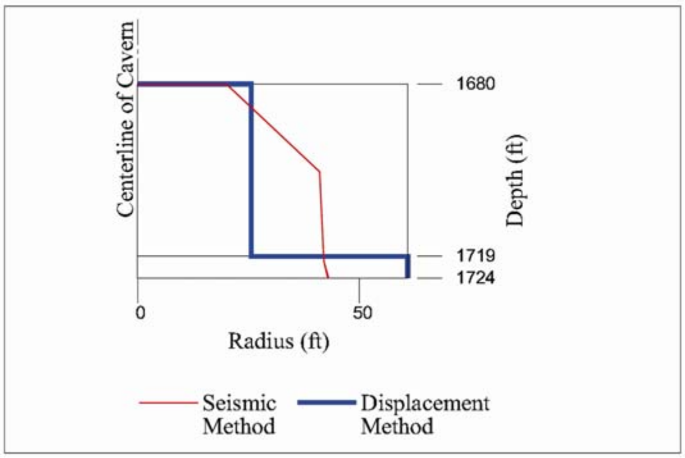

Figure 8. Comparison of Top of Cavern Shape from the Seismic and Displacement Methods

Conclusions

- The Downhole Seismic Reflector Tracing (TRT™) provided sufficient data to estimate the shape of the entire solution mining cavity.
- The TRT™ test survey provided images of the underground features within the solution mining zone that correlated with geological data.
- The configuration and horizontal dimensions of imaged reflective anomalies were consistent with the most likely development and horizontal extent of solution mining related caverns and structural changes.
- The horizontal dimensions of imaged anomalies assumes an average circular cavern shape as the array of sources and receivers placed in a single vertical well lacks the directional resolution in the horizontal plane.

- The survey results demonstrated the viability of the TRT™ application for imaging the effects and extent of solution mining in rubble-filled caverns.

- The volumes calculated from the shape interpreted from the downhole seismic model compares favorably with the historical production data. The seismic model was 6% greater than the historical production. The seismic model compares favorably with the displacement volumes. The total displaced gallons were 9.4% greater than the volume predicted by the seismic model.

- The shape of the cavern indicates that solution mining was focused in the zones of higher-grade nahcolite and the injection horizon.

- The maximum diameter of the cavity was 58% larger than the estimated average cavity diameter assuming a uniform cavity diameter.

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