SOLUTION MINING RESEARCH INSTITUTE
3336 Lone Hill Lane
Encinitas, California 92024
USA
Country Code: 1 ♦ Voice: 858-759-7532 ♦Fax: 858-759-7542
E-mail: smri@solution mining.org ♦ www.solutionmining.org

Research Project Report
No. 2004-1-SMRI

STATE-OF-THE-ART REVIEW OF EXISTING AND NOVEL METHODS FOR MAPPING SOLUTION-MINED STORAGE CAVERNS

Prepared by:

Larry K. McDonald and Ken E. Davis
Subsurface Technology, Inc.
Houston, Texas, USA

Ralph M. Gaertner
DEEP. Underground Engineering GmbH
Bad Zwischenahn, Germany

Leo Fox
Phoenix Geophysics, Limited
Toronto, Canada

John Camperman
Naval Surface Warfare Center - PC
(Previously Coastal Systems Station)
Panama City, Florida USA

June 2004

EXECUTIVE SUMMARY

Subsurface Technology, Inc. and their subcontractors, Coastal Systems Station, DEEP. Underground Engineering GmbH, and Phoenix Geophysics Limited, were contracted by the Solution Mining Research Institute to conduct a state-of-the-art review of existing and novel methods for mapping solution-mined storage caverns.

This report presents descriptions of methods that have been used, or have the potential for use, in measuring a cavern's actual geometry. Included are technical descriptions of the selected methods, discussions of operational procedures, cost estimates, and resources for procuring the services to implement the methods. The methods discussed in the report are:

- Sonar
- Laser
- Magnetotellurics (MT)
- Electromagnetic Seismic Reflection
- Light Detection and Ranging
- Volumetric Calculations
- Surface Microgravity
- Borehole Microgravity
- Three-Dimensional Full Tensor Gradient
- Single-Well Seismic Imaging
- Crosswell Seismic Imaging

From this study, it was determined that sonar remains the state-of-the-art method for mapping solution-mined storage caverns, both gas and liquids.

Laser technology has successfully been demonstrated in air-filled caverns and in mine shafts under atmospheric conditions. Currently, the application of laser technology in a gas environment under pressure is not possible due to the pressure limitations of the laser housing. Additionally, light is heavily dampened in environments containing hydrocarbons and the wavelength of the laser source lies within the range of the absorption spectrum of natural gas; thus, limiting the acquisition of usable data.

Based on the apparently conflicting information available, it is not possible to be certain whether magnetotelluric technology (MT) can be used for cavern mapping. Neither its proponents, nor its opponents, have presented a convincing, objective, thorough, and scientifically clear argument.

To resolve the problem additional work is proposed as outlined below:

- Further investigation to try to decide the optimum equipment and measurement configuration, including behaviour of the electromagnetic (EM) wave in the intermediate regime (between propagation and conduction) where the loss factor is approximately 1.

- Acquisition of a "test" data set (with conventional MT equipment) above a known cavern which would measure the usual 5 components of the EM field across a relatively wide frequency range (from hundreds of seconds to 10 kHz).

- Analysis of that data set to try to elucidate the principles involved and to come to a conclusion.

Although there is a relative low impedance difference between liquid hydrocarbons, i.e. diesel or oil and salt, the transition zone of the fluid to the salt body can be interpreted depending on the frequency of the ground penetrating radar (GPR) sonde, the material parameters (permittivity and conductivity), and the geometrical dimensions of the structure. Possible reflections will later be interpreted in the post-processing of the data as cavern walls, geological structures, layers, etc. The wavelength of a typical GPR tool is approximately in the one-meter (3-foot) range in salt. Therefore, the resolution of the GPR tool will be in the same range.

Low signal strength may tend to constrict strong interpretations which are needed to construct the sought after three-dimensional model. It has been shown that the use of crude oil instead of diesel raises the impedance differences, resulting in more discernable reflections. Measurements in natural gas caverns have not yet been conducted. However, it is assumed that the signal quality will decrease with an increase in the water content of the gas.

In order to achieve information on leached areas, hidden spaces or small-scale structures that cannot be detected with conventional sonar surveys, a higher electromagnetic frequency of about 100 MHz has to be used. However, higher frequencies results in a smaller cavern radius that can be measured, and is not applicable in many caverns due to their size. In order to visualise the geometry of a cavern, the application of an electromagnetic sonde from a neighbouring borehole within range of the radar waves (approximately 150 meters (492 feet)) is currently being investigated.

Light detection and ranging is a promising technique that can be used to improve in-cavern mapping, especially in gas-filled caverns of any practical size. Light detection and ranging might also provide an option for mapping smaller, liquid-filled caverns. A mapping system that utilizes both light detection and ranging and sonar to map solution-mined caverns is potentially feasible.

State-of-the-art sensors, positioning and navigation systems, and data processing systems are available and can be configured into such a system.

Specialized radar has potential for cavern mapping and was investigated in the 1980s (Castle 1988, 1989). However, no additional information regarding cavern radar work following 1989 was found in literature searches and, therefore, specialized radar is not addressed in this study. In addition, conventional radar systems are expected to be problematic due to attenuation in liquids and reverberation (multiple path echoes) in gases.

Three-dimensional seismic surveys were also considered for incorporation into this study. However, it was determined from conversations with seismic experts that although three-dimensional seismic is an invaluable tool for determining overall salt mass and boundary conditions, the resolution of three-dimensional seismic is not sensitive enough to map solution-mined storage caverns to the degree required by cavern operators. Vertical resolutions with three-dimensional seismic are on the order of 3.1m to 4.6m (10 feet to 15 feet), while horizontal resolutions are on the order of 9.5m to 12.2m (30 feet to 40 feet). However, four-dimensional time-lapse seismic technology is currently being evaluated and may hold promise for mapping solution-mined storage caverns to the degree required by solution-mined cavern well operators, as well as mining regulatory bodies.

Technologies found to hold promise for future research and/or testing were surface microgravity, borehole microgravity, three-dimensional full-tensor gradient, single-well seismic imaging, and crosswell seismic imaging.