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FEASIBILITY STUDY FOR THE STORAGE OF COLD COMPRESSED NATURAL GAS (CCNG) IN UNDERGROUND SOLUTION-MINED BEDDED SALT CAVERNS

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Abstract

This paper summarizes results of a feasibility study for the storage of cold compressed natural gas in underground, solution-mined, bedded salt caverns. The cold compressed gas storage concept involves storing cold gas in an existing salt cavern under pressure and removing the gas during peak demand times. More gas can be stored in a fixed volume by lowering the gas temperature and increasing its pressure. This produces an economic advantage.

The performance of solution-mined caverns is governed by the geomechanics of the rock. To safely store gas, the rock must have low permeability and be free of ruptures and fractures that extend for large distances. The cavern must remain stable to avoid loss of storage volume and prevent any collapse that threatens the integrity of the riser pipe system.

Performance of a cavern depends on the physical and mechanical properties of the surrounding rock. This work included series of laboratory tests on core samples of dolomite and saltstone from a site in New York to measure the effect of low temperatures on their properties. The test results conclusively show that chilling the rock to temperatures as low as -150º F does not degrade the mechanical and physical properties of the saltstone and dolomite.

Advanced thermo-geomechanical analyses were performed to determine if a salt cavern can remain stable under the combined effects of cold temperature and high pressure. The analyses show that thermal compression of the rock may produce cracks along vertical planes that radiate outward from the cavern walls for distances of 200 to 300 ft. However, the cavern walls remain stable and gas tight. The analyses also show that the most critical time for cavern stability is during initial cooling when the tensile stresses are the greatest. Faster cooling appears to cause more cracking. Despite this cracking, the cavern remains stable because the rock remains uncracked in the vertical and radial direction away from the chamber and vertical stresses within the cracked zone are safely transferred to rock outside the tensile zone.

Introduction

This paper describes some of the results of a feasibility study for the storage of cold compressed natural gas in underground, solution-mined, bedded salt caverns. The work was performed as part of a research and development contract conducted by Vandor & Vandor Alternative Energy Solutions of New York under the sponsorship of New York State Energy and Research Agency.

The cold compressed gas storage concept involves storing cold gas in a salt cavern under pressure at cold temperatures and removing the gas during peak demand times. By cooling the gas, 3 to 4 times more energy can be stored in a given volume than comparable warm pressurized gas storage. A patent pending process for cooling the gas and recovering cold from the released gas makes the concept economically feasible.

The specific case studied involved a solution cavern to be mined in saltstone located some 3,000 ft below the ground surface below a ceiling of dolomite. The cavern will be cooled from its ambient temperature of +110° F to -150° F over a period of several months to avoid thermal shock, then filled and emptied on a typical 30-day cycle. When near full, the temperature will be -150° F under a pressure of 2,000 psi (1500 psig at ground surface). Temperature may rise to -100° F and pressure of 3,000 psi (2,500 psig at ground surface) as the gas is heated by the surrounding rock. During the most rapid withdrawal the temperature may drop to -190° F and pressure to 640 psi (140 psig at ground surface). These temperatures and pressures were considered as the extremes for thermo-geomechanical analyses. Actual temperatures and pressures will depend on the energy balance for the final design.

The study examined the feasibility of the concept of compressed, cold gas storage and developed the requirements for a field demonstration to prove the technology.

Geomechanics Issues

The performance of solution-mined caverns is governed by the geomechanics of the rock and the fluid contained therein. To safely store gas, the rock must have low permeability and be free of ruptures and fractures that extend for unknown distances. The cavern must remain stable to avoid loss of storage volume and any collapse that threatens the integrity of the riser pipe system. These requirements lead to the following primary questions about the possible geotechnical performance of cavities in saltstone with a roof of dolomite:

1. How will the specific geologic strata and cavern shape affect stability of these saltstone caverns?
2. What is the behavior at the saltstone-dolomite interface where there is the potential for differential slip that results from the difference in mechanical properties of these two materials?
3. How do low temperatures affect the mechanical properties of saltstone and dolomite?
4. Will the compression from cooling of the saltstone and dolomite create tensile fractures that cause instability of the walls and roof of the cavern?
5. Will the gas remain confined within the saltstone?

There are several factors that control whether a cavern is stable or unstable. These factors interact and combine to make assessment of stability unique for each cavern. The principal factors are reviewed and discussed below.

Mechanical properties of the rock around caverns in saltstone.

Mechanical properties refer to the strength and modulus of the rock and permeability of the rock to gas, fluid and heat for each rock type in the vicinity of the cavern. These properties depend on rock type, stress levels, temperature, fluid pressures within the pores, and soundness of the rock. The mechanical properties of the saltstone and dolomite directly control stability/instability of each cavern.

Saltstone is typically sound rock free of large fractures. The mechanical properties of the intact rock control the behavior of the rock mass. Saltstone is generally comprised of crystals of salt with face dimensions up to several mm. Other minerals may exist at the boundaries between crystals. At a crystal-sized scale, the properties of salt can differ considerably but these differences disappear at scales of feet and meters. Saltstone exhibits creep. (Creep is strain over time of an element that is under a constant state of stress.) Creep can cause substantial inward movement of unpressurized caverns in saltstone. Creep can heal fractures that may have developed over geologic time.

Saltstone beds and domes are isolated from water sources that promote the growth of fractures within rock (provided they have not been penetrated by previous drilling). The strength and stiffness of saltstone are a function of the stresses and temperatures applied to the rock. Decreasing temperature typically increases strength and stiffness of rock, but little data exist in the engineering literature for these properties of salt below -20° F. Creep may affect the strength and stiffness of rock. Saltstone has one of the highest creep rates of all rock types. Saltstone may undergo significant creep when the ambient stresses are changed. Creep can reduce or increase shear stress intensity[1] depending on the specific geometry, temperature and stress conditions. Creep rate decreases with decreasing temperature but this effect has not been well studied at cryogenic temperatures.

Reasonably good information exists on the parameters for numerical modeling of saltstone creep, especially at elevated temperatures. However, little information exists on the strength and creep characteristics of salt for sub-zero conditions.

Dolomite is typically stronger and stiffer than saltstone. Its creep rate is significantly less than that of saltstone. Creep of dolomite is generally considered insignificant. Dolomite may contain inclusions of other materials and may be fractured. These defects may reduce the strength and stiffness of the rock mass compared to those for intact dolomite. A major consideration for dolomite is whether fractures and inclusions exist that weaken its overall strength. Little information exists on the strength and stiffness properties of dolomite at sub-zero conditions.

Mechanical tests had previously been made at a site considered a candidate for the field demonstration cores of saltstone and dolomite indicated sound saltstone and dolomite, although some of the dolomite contained salt and pyrite-filled fractures with innerbeds of shale. These data gave the following useful mechanical properties for the saltstone and dolomite applicable to the site for room temperatures.

Table 1: Mechanical Properties at Bath Petroleum Site

Property	**Saltstone**	**Dolomite**	**Shale**
Density	115 – 119 pcf	170-174 pcf	164 pcf
Tensile Strength	NM	NM	900 – 1380 psi
Triaxial Strength	NM	c=5,980 psi ϕ=33.5°	NM
Young's Modulus	4 x 10^6 psi	8.0 – 8.6 x 10^6 psi	7.8 x 10^6 psi
Poisson's Ratio from seismic velocity	0.20 – 0.22	0.15 – 0.25	0.23

NM – not measured

RESPEC[2] summarized mechanical properties on salt and shale from a well located near Cayuta, NY. Their report gives the following useful test results for saltstone and shale. They did not test dolomite.

Table 2: Mechanical Properties at Cayuta, NY Site

Property	**Saltstone**	**Shale**
Unconfined Compressive Strength	NM	15,300 – 18,600 psi
Tensile Strength (mean and SD)	283 ±46 psi	700 ±315 psi (⊥ to bedding) 1375±400 psi (∗ to bedding
Triaxial Strength	c=610 psi ϕ=53.4°	c=860 psi ϕ=65°
Young's Modulus (unload and reload)	3.0 – 4.4 x 10^6 psi	3.7 – 6.9 x 10^6 psi
Poisson's Ratio	0.29 – 0.50	0.12 – 0.29
Thermal Conductivity (W/m°K)	$6.7*(T/253.15K)^{-1.8}$	NM

NM – not measured

Most of the results in Table 1 are for different material properties than those in Table 2. The common elements are values of Young's Modulus. Values for Young's Modulus of saltstone are similar at the two sites as are the values for shale. Values for tensile strength of shale are similar for the two sites. Work by Rickard (1969)[3] concluded that these materials are part of the Upper Silurian Salina Group formed in the Appalachian basin in New York, Pennsylvania and Ohio. Therefore it is reasonable to combine results from the two test programs into one set of material properties for the saltstone, dolomite and shale at 3000 ft depth in New York.

RESPEC did limited testing of the effects of lower temperature on cores samples of saltstone. Comparing test results from specimens at -30º C with those at room temperature, they concluded that:

- The elastic moduli of the salt were relatively unaffected by the lower temperature.
- Strain at failure is reduced at the lower temperature.
- The ultimate strength and dilation behavior were unaffected by the lower temperature (although the data set is very limited because some specimens did not fail).
- Creep rate was reduced by 75% by lowering the temperature from 40º C to -20º C.

These data gave us sufficient information on the mechanical properties of saltstone, dolomite and shale in the intended field test vicinity to support analyses for conceptual design except under cryogenic conditions.

Static stresses from forces of gravity prior to creation of the cavern.

The ratio of geostatic horizontal stress to vertical stress in the saltstone and dolomite before creation of a cavern affects the magnitude and distribution of stresses around the cavern. A high ratio can create large compressive stresses in the roof and floor of a vertical cavern. A low ratio can produce ideal conditions for hydraulic fracturing in which the cavern pressure creates vertical fractures within the intact rock along vertical planes outward from the cavern. Very few data exist on the ratio of horizontal to vertical geostatic stress in saltstone. This ratio could be as low as 0.5 and as high as 1.5 or more with the actual value dependent on specific site conditions. Obert (1962) reported a value of 0.95 for one saltstone. Site-specific values are best determined by in-ground measurements of lateral stress. Since this was not a part of feasibility study, the alternative was to evaluate all available data for lateral stress in saltstone and bound the lowest and highest expected value for this site.

Previous pressure testing of a well at the candidate site showed no gas leakage at a pressure of 2600 psig. This indicated that the lateral stress must be at least 0.88 times the vertical stress for the salt at this site. For the present work a ratio of horizontal to vertical geostatic stress in the saltstone of 0.9 was used as a best estimate of the likely value for the candidate site.

Shape and orientation of the cavern relative to site geology.

Underground openings with rounded corners produce more favorable conditions for rock stability than openings with sharp corners.[4] A cavity with rounded corners and an arching roof will have significantly lower shear stress intensity than a trapezoidal-shaped cavity like that analyzed by RESPEC(2001[5]) for the Avoca NY site. Caverns crowned with dolomite will tend to be stronger than caverns isolated in salt only. The effects on shear stress intensity of cavity shape and orientation relative to geologic conditions are best determined by advanced numerical analysis using the actual cavern dimensions and shape.

Gas or fluid pressure inside the cavern.

The operating pressure of gas or fluid in the cavern relative to the rock stresses affects the stability of the cavern. Low cavern pressure increases the inward movement of the sidewalls from saltstone creep and can over time cause significant reductions in the storage capacity of a cavern. High cavern pressure can cause hydraulic fracturing of the rock walls which generates cracks in intact rock that extend for tens to hundreds of feet and increase the risk for significant leakage of gas with associated safety hazards. A vertical stress in the saltstone at a depth of 3,000 ft was estimated at around 2,900 psi. The horizontal stress at this depth would be approximately 2,600 psi. Cavern pressure should be kept below 2,600 psi to avoid the possibility of hydraulic fracturing. Pressure tests on the wells at the site by others demonstrated that they hold gas at pressures up to 2,600 psi without significant loss. The pressure of the gas should not exceed 2,600 psig in the cavern (2,100 psig at ground surface) to avoid the possibility of hydraulic fracturing of the rock mass.

The stress (pressure) difference between the rock and the gas will affect the shear stress intensity around the cavern. If the rock has a geostatic stress ratio (ratio of horizontal stress to vertical stress in saltstone before making the cavern) of less than 1, this stress difference is less significant. The importance of gas pressure relative to geostatic stresses is determined by advanced numerical analysis.

Gas permeability of the rock

Permeability affects the distribution of gas pressure within the rock, which may affect the strength of the rock. Saltstone and dolomite are normally impervious to fluid and gas flow, unless they contain fractures. Previous work has shown that the flow of gas from cavities in unfractured saltstone and dolomite is negligible. Pressure tests on the wells at the site have demonstrated that they hold gas at pressures up to 2,600 psi without significant loss. Five specimens from the candidate site had been previously tested to pressures up to 3,000 psi without gas breakthrough. This indicates that the salt has a low permeability to gas.

Temperature of the cavern contents

Ambient rock temperature at 3,000-foot depth is about +110° F. The temperature of the CCNG in the cavern can vary from -100° F to -190° F. Rock contracts when it is cooled. If the rock is unconstrained and free to expand or contract (such as a block sitting on a table), the dimensions of the block decrease but there are no stress changes within the specimen. Hence salt crystals or a chunk of saltstone can withstand the conditions of liquid nitrogen without distress, provided they are cooled slowly enough to avoid large temperature differentials to develop within the specimen. This fact permits salt crystals to survive large extremes in temperature; such as the 200° F daily temperature swings on the surface of Mars, as the current NASA missions are demonstrating. NASA is using special instruments to look for salt crystals as indicators of the past presence of water. NASA must believe that salt can survive these extreme temperature changes over millions of years, or else they would not have devoted so much money to looking for them on Mars.

To confirm this supposition, a piece of rock salt from the site in a bath of liquid nitrogen. Comparison of photographs before and after the immersion showed no visible change in the pieces of saltstone and dolomite. To seasoned mineralogists and materials engineers this simple test may seem like an obvious waste of time, but it provided compelling visual evidence for the non-technical people that are inevitably involved.

When a material is constrained from changing dimensions and cooled, a tensile stress proportional to $E\alpha\Delta T$ develops. E is the Young's Modulus of the rock for which we have good information from the SAIC tests and the RESPEC work at Avoca. α is the coefficient of thermal expansion of the rock for which we have good information down to temperatures of -20° F. ΔT is the temperature change, which is controlled by the design temperature for the cavern; the rate of temperature change within the cavern; and the coefficient of thermal diffusity of the rock. These values are available from RESPEC tests and published work by others. The following table gives typical values of these parameters for the test site and calculated changes in tangential normal stress for a temperature decrease from 110° F to -150° F.

Table 3 gives results from a simplistic calculation that ignores the existing stress state in the rock prior to cooling, assumes elastic behavior with no tensile cracking, assumes fully constrained conditions, and uses moduli for above-zero conditions. Nevertheless, it shows the potential magnitude of the decrease in tangential normal stress around the cavern wall from cooling. The tensile strength of saltstone and dolomite is a few hundred psi. Clearly, a large temperature drop in a totally constrained condition can cause enough thermal

Table 3: Tensile stresses from elastic cooling of rock				
Material	E Psi	α per ° F	ΔT ° F	Change in stress Psi
Saltstone	4×10^6	2×10^{-5}	-260	21,000 tension
Dolomite	8×10^6	4×10^{-6}	-260	8,000 tension

contraction to create cracks by tensile failure within rock. Tensile cracks from cooling will develop along planes normal to the surface of the cavern but are not expected along planes parallel to the surface of the cavern. We know this mechanism occurs in nature. Parts of the Northwest United States are covered with columnar basalt. These columns can reach tens to hundreds of feet in height and are polygonal in shape. Each column was created by cracks that formed as molten lava cooled from the surface downward, a process that is mathematically similar to cooling the cavern walls from the inside. Jagla[67] has shown using energy considerations that such cracking should form into polygonal shapes as shown in Illustration 1. However to our knowledge, the engineering mechanics for predicting the characteristics of tensile cracks in cavern walls from large decreases in temperature and design procedures to deal with such cracks have not been well developed.

Cracks radiating away from the cavern wall in unfractured rock should not affect the functionality of the cavern. These cracks will close when the temperature is increased and reopen when it again decreases. However over time the cold temperature moves deeper into the rock, causing the cracks to deepen. At some point the cracks could become sufficiently deep that the weight of the block between cracks exceeds the rock's tensile strength and the block falls out. This could begin a sequence of slabbing of rock blocks off the walls of the cavern. However, provided the existing rock mass is of very good quality with few to no existing fractures, this process should not produce a sudden complete collapse of the cavern, nor loss of gas. Tensile cracks from cooling may also occur in the dolomite of the roof. However the tensile strength of the dolomite is enough to hold cracked blocks of dolomite in place for crack depths of hundreds of feet. Additionally, the compressive stress in the roof from gravity forces will tend to limit the depth of cracks in the roof. Without advanced numerical analysis, it is not clear how these cracks will affect the distribution of stress around the cavern from gravity forces. This is the main reason that numerical analyses which couple stresses from gravity with those from thermal causes were required in the feasibility study.

Crack pattern computed by Jagla from thermal cooling in an isotropic stress field.

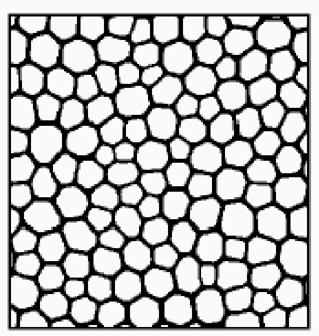

Illustration 1: Crack Pattern in Basalt

An immediate, large drop or increase in temperature can cause materials to spall. For example, spalling may occur when a blowtorch is directed at a localized point on a piece of rock. Spalling may also occur if a stream of very cold nitrogen gas is directed at a localized point on a piece of rock. Spalling is caused by extreme temperature gradients within a small area and a small thickness that create localized concentrations of tensile strains, perhaps accompanied by high internal gas pressure, or ice pressure, when water is present in the rock. Spalling is avoided by preventing extreme, rapid, localized changes in temperature of the rock. Spalling of the cavern wall due to adding or removing gas from a cavern is not expected to occur due to the relatively long time it takes to alter the temperature inside the cavern.

Lab Testing for Material Properties

As described earlier, sufficient and representative information was available on the mechanical properties of saltstone and dolomite at temperatures above -20° F to evaluate the geomechanical behavior of caverns produced by solution mining with filled with CNG. However no information was available on the mechanical properties of saltstone at temperature below -20° F. A limited lab program was undertaken to quantify the effects of low temperature on the important geomechanical properties of the saltstone.

Cores of saltstone and dolomite were obtained from a depth of 3000 ft at a site in Western New York. These cores were approximately 3½ inches in diameter and 12 inches long. They were obtained approximately 10 years ago, were wrapped in plastic wrap, and had been held at nominal room temperature since. These samples had been removed from an environment where the stress level was thousands of psi, the temperature was 110° F and the potential for moisture change was essentially zero to an environment where the stress level was zero, the temperature was ambient conditions, and moisture was available from the surrounding air. While plastic wrap may slow down exchange of moisture from the air to a sample over a few days, it is not effective at controlling moisture exchange over months or years. Visual examination showed that efflorescence of salt had occurred on the outer surface of the cores. It is possible that these samples have experienced changes such that the specific results of mechanical tests performed on them to measure mechanical parameters could be misleading or questioned. In general, these changes, if they have occurred, could degrade the mechanical properties of the saltstone and dolomite, but by an unknown amount. However, simple tests could be used to indicate the relative effects of low temperatures on mechanical properties of these cores. Mechanical tests on specimens cooled to temperatures between -20° F and -150° F would indicate in a relative sense how the mechanical properties of saltstone and dolomite change in cryogenic conditions.

Smaller specimens were cored from the 3½-inch diameter saltstone cores. The 1-inch cores were cut to 2-inch lengths to form test specimens. Each specimen was instrumented with strain gauges to determine Young's modulus and Poisson's ratio and a temperature sensor. The specimen was encased in foam insulation with the top and bottom open. The foam helped slow the rate of warming while the specimen was in the compression machine for testing. Each specimen was slowly cooled to the desired test temperature, removed from the cooling chamber and tested immediately for unconfined compressive strength. Measurements from the instruments provided unconfined compressive strength, Young's Modulus and Poisson's Ratio for each specimen.

Table 4 gives average values of measured unconfined compressive strength on three specimens of dolomite. The measured values are comparable to values given in the literature. The results show a consistent and significant increase in the compressive strength of the dolomite with decreasing temperature.

Table 4: Compressive Strength of Dolomite

Temperature	Average Unconfined Compressive Strength, psi
70º F	7,630
-100º F	12,000
-150º F	15,000

Table 5 gives the results of Young's Modulus and Poisson's Ratio measurements on the same three specimens. The results show no significant effect of lower temperature on the Young's Modulus of the dolomite. The results for Poisson's Ratio show considerable scatter with no trend. Measured values for Young's Modulus are similar to those given in Tables 1 and 2 and values reported in the literature.

Table 5: Elastic Parameters

Temperature	Average Young's Modulus, psi	Average Poisson's Ratio
70º F	5.8×10^6	0.33
-135º F	5.1×10^6	0.09
-175º F	5.8×10^6	0.47

Table 6 gives the results of tests to measure tensile strength by the splitting method. Like compressive strength, the tests show tensile strength of dolomite increasing with decreasing temperature. The results show a consistent and significant increase in the compressive strength of the dolomite with decreasing temperature. Measured values at room temperature are typical of those given in the literature.

Table 6: Tensile Strength of Dolomite

Temperature	Average Tensile Strength, psi
70º F	1,300
-100º F	1,700
-150º F	2,100

The study had intended to do similar tests to measure the effect of cold temperature on strength of saltstone. However the crystal size of the salt was too large for such small specimens to give meaningful results. Insufficient core was available to run the tests on 3½-inch diameter core. Point load tests on pieces of broken core is broken between two rounded steel points were substituted for unconfined compression tests. Table 7 gives the results of average point load strength. They do not follow a consistent trend with decreasing temperature. The inherent variability of the point load test may be masking the effect of temperature.

Table 7: Point Load Strength of Saltstone

Temperature	Average Point Load Strength, psi
70º F	95
-100º F	117
-150º F	92

Table 8 gives the average of results of tensile tests run on specimens of saltstone. The values show a slight increase in average tensile strength with decreasing temperature. The values are consistent with values reported in the literature of similar order to those in Table 2.

Table 8 Tensile Strength of Saltstone

Temperature	Average Tensile Strength, psi
70º F	158
-100º F	172
-150º F	183

In summary the laboratory tests performed on core samples of saltstone and dolomite from western New York showed:

(1) Fragments of saltstone and dolomite experienced no visible damage from immersing them in liquid nitrogen at -240º F.
(2) Compressive strength of saltstone and dolomite increased as temperature was decreased from room temperature to -150º F.
(3) Tensile strength of saltstone and dolomite increased as temperature was decreased from room temperature to -150º F.
(4) Stiffness of dolomite did not change significantly as temperature was decreased from room temperature to -150º F.

The test results conclusively show that chilling the rock to temperatures as low as -240º F does not degrade the mechanical and physical properties of the saltstone and dolomite. In fact cryogenic conditions may increase their compressive and tensile strengths. Further testing of saltstone at cold temperatures should be carried out to further define the effects of low temperature on strength and compressibility of saltstone for optimizing the design of cold storage facilities in salt.

Analyses

This project involves complex interactions of stresses and strains created by the forces of gravity, the shape of the cavern, the mechanical properties of the saltstone and dolomite, the pressure and temperature of the gas inside the cavern, and the effects of low temperatures on the behavior of saltstone and dolomite in the cavern walls and roof. These complex interactions are coupled and non-linear. It is impossible with limited resources to combine all of these factors into one bench-scale laboratory test. It is also virtually impossible to examine these complex interactions with hand calculations. It is clear that parts of the rock will experience plastic behavior, which greatly reduces the value of hand calculations based on elastic theory. These interactions can only be realistically examined with advanced numerical analysis methods.

Complex geomechanical problems are solved with complex numerical methods that use the so-called “finite element method”. In this method, the geometry is subdivided into many small pieces or elements. Each piece has a shape, stress-strain properties and permeability. Each piece has boundary conditions in terms of stress and displacement around the element’s boundary. Fundamental laws of mechanics require that each piece be in static equilibrium, that its stress state obeys a valid stress-strain relationship, and that mass be conserved and energy minimized during distortion from added forces. Earthen materials complicate the analysis because they can be three-phase (solid, liquid and gas) and exhibit non-liner and plastic behavior. The FLAC software was chosen to do the analysis because it has the capability of modeling development of geostatic stresses, creation of the cavern, application of internal gas pressure and analysis of heat flow and its effects on stresses and strains in the cavern wall, all in a three dimensional geometry. Figure 1 shows the model of finite elements assembled for this analysis. Each color represents a different geologic material.

Figure 1 shows the geometrical model for *FLAC3D* for a 150 ft diameter cavern, 500 ft high, with its arch 3000 ft below the ground surface. The geologic profile was simplified to its essential elements:

Material	**Depth, ft**	**Used in this Work**
Overburden	0-2900 ft	overburden
Rock A	2900 – 2950 ft	dolomite
Rock B	2950 – 3000 ft	dolomite
Salt A	3000 – 3240 ft	saltstone
Salt B	3240 – 3260 ft	saltstone
Salt C	3260 – 3500 ft	saltstone
Rock C	3500 – 3600 ft	dolomite
Rock D	3600 – 4000 ft	dolomite

Rock A and B can be similar or different materials to permit examination the effect of thickness of a single dolomite layer on cavern stability without rebuilding the model. Also Salt B was introduced to allow the effects of a shale or dolomite layer within the cavern to be examined. Rock C and D can be similar or different materials to permit examination of the effect of thickness of the dolomite layer at the bottom of the cavern. For the analyses in this paper, Rock A and B are the same material, Rock C and D are the same, and Salt A, B and C are the same.

The analysis applied the bilinear/strain softening model to permit simulation of the effects of joints developing within the rock. As shown in Illustration 2, after the shear stress reaches the tensile strength of the rock, the allowable tensile stress on that element is reduced to zero. However the element may later develop compressive shear stresses until the compressive shear strength is reached.

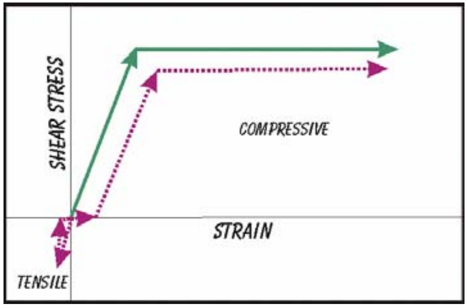

Illustration 2: Stress-Strain Model

The analyses used the bilinear Mohr Coulomb strain-softening model with the parameters given in Table 9:

Table 9: Material Parameters for Stress and Strain

Material	c, psf	Phi (degrees)	Tensile Strength, psf	Young's Modulus, E_i, psf	Poisson's Ratio
Overburden	860,000	33	150,000	$8 * 10^8$	0.22
Rock	860,000	33	300,000	$8 * 10^8$	0.22
Salt	100,000	42	40,000	$7.5 * 10^8$	0.33

Temperature varied with depth using the following expression:

$$T = 50 + 0.0185*Z \quad \text{with T in °F and Z in feet}$$

This is a commonly used expression of temperature with depth for deep applications. Table 10 provides the thermal parameters for the rocks modeled in the analysis. These values were obtained from a review of published information.

Table 10: Thermal Parameters for Rock

Material	Coefficient of thermal expansion, /°F	Specific Heat, BTU/(lb_{mass}-°F)	Thermal Conductivity, BTU/foot-day/°F	Thermal Diffusity, ft^2/day
Overburden	$4*10^{-6}$	0.2	25	1
Dolomite	$4*10^{-6}$	0.2	25	1
Shale	$4*10^{-6}$	0.2	25	1
Saltstone	$2*10^{-5}$	0.2	180	7

Note that saltstone is five times more expansive and 7 times more conductive than the other rocks. This means that saltstone expands and contracts with changes in temperature five times more than other rock and it conducts heat seven times as fast as other rocks. These differences amplify the effects of thermal stresses on the stress intensity around a salt cavern.

These analyses did not model creep. Normally creep of salt can be a significant factor. However available information suggests that lower temperatures will significantly reduce the creep rate but we have no specific data for the temperature range of –100 to –190° F considered here. Creep was considered to be of secondary importance in this problem since the cavern will spend most of its life with a high internal gas pressure. To the extent that creep occurs it will generally produce a favorable result in that it will tend to close up and heal whatever tensile cracks form in the saltstone from the thermal contraction.

Geostatic stresses were computed from known unit weights for the materials given in Table 11 and a coefficient of lateral stress of 0.9. Water pressure in the rocks was taken as zero.

Table 11: Unit Weight of Materials

Material	Unit Weight, pcf	K_0
Overburden	142	.9
Salt	135	.9
Dolomite	142	.9
Brine	75	1
Liquid gas	26.5	1
Compressed gas	23	1

The stress distribution within a geologic medium depends on the geologic history and the exact load path that the materials go through to reach a certain state. Consequently advanced numerical modeling requires the calculation sequence to follow the significant elements of the development and operational history of the site. The significant steps for this site were duplicated in the analysis are as follows:

1. Create geologic geometry.
2. Calculate initial stresses with level ground and no cavity and with thermal gradient applied.
3. Remove material in cavity while applying a boundary pressure to the cavern equal to the pressure of the brine with total head of brine at ground surface. (i.e. at 3000 ft depth, brine pressure will be 1,560 psi and at 3500 ft it will be 1800 psi.)
4. Replace brine from 3,000 to 3,500 ft depth with gas at –150° F under pressure of 1500 psi over a period of 8 months.
5. Maintain gas mass for two months during which time temperature rises to –100° F and pressure rises to 2500 psig.
6. Remove gas to pressure of 140 psig over 10 days. Temperature drops to –190° F.
7. Refill cavern with gas to pressure of 1500 psig at -150° F over 20 days.

Specific values of operating temperature and pressure were chosen to cover the anticipated extremes. Actual operating values in a commercial cavern may be less extreme and therefore less stressful to the cavern walls.

Results of the FLAC analyses are computations of stresses, displacements and temperatures at many points in space and time. The information is massive. We have selected some typical plots to summarize the significant elements and findings from the analysis. *FLAC uses positive values for tensile stresses and negative values for compressive stresses. Positive z displacement is upward. Positive radial displacement is outward.*

Figure 2a shows a side view of the cavity vicinity. About 400 ft of rock above and 400 ft of rock below the 500 ft high chamber are shown. Temperature in the vicinity of the cavern is nearly constant at 110º F, so the left side of the figure, which we will use to show temperature contours, is left blank. The right side of Figure 2a shows vectors of displacement caused by excavating the cavern. The arrows indicate the direction of movement. The length of the arrows indicates relative magnitude of displacement. The colored zones represent areas with similar magnitudes of displacement. The displacements are total values that accumulate from the beginning of cavern excavation. The maximum displacement occurs at the bottom of the cavern and equals 0.015 ft upward. The sides of the cavern move inward approximately 0.05 ft. These movements result from the stress relief that occurs when rock at a unit weight of 135 pcf is replaced with brine at a unit weight of 75 pcf.

Figure 2b shows contours of the radial stress and tangential stress for the same side view. Figure 2c shows contours of the vertical stress and major principal stress for the same side view. Principal stresses are defined as the normal stresses that occur on planes with no shear stress. Half of the difference between major principal stress and minor principal stress equals the maximum shear stress at a point, which cannot exceed the material's shear strength. FLAC defines the most positive (or least negative) principal stress as the major principal stress. Hence a positive value of the major principal stress indicates development of tensile stresses. Figures 2b and 2c show relatively smooth contours of stress with no zones of tensile stress.

Figures 3a, 3b, and 3c give the same side views of temperature, displacement and stresses after the brine has been replaced with gas and the gas cooled to -150º F and pressurized to 1500 psig over 260 days. The figures show the results at the end of 260 days. The temperature contours in Figure 3a show that a sub-zero zone extending outward from the chamber wall approximately one chamber diameter (150 ft). The right side of Figure 3a shows the total displacements at 260 days of cooling. These displacements are total values that accumulate from the beginning of cavern excavation. Since the computed displacements for cavern excavation were relatively small (0.015 ft); the displayed values are essentially those that result from filling the chamber with gas and cooling the wall down to -150°F. The computations show up to 0.8 ft of outward movement of the cavern wall. These result from expansion of the cavity as the internal pressure is increased from that of brine at 1,200 psi to gas at 2,000 psi (1,500 psi at ground surface) and the confined contraction of the saltstone as its temperature is decreased from +110° F to -150° F. The displacement pattern is a complex one due to the superposition of displacements from the increase in cavern pressure and the reduction of temperature. Importantly, the computations converged to a numerically stable solution and the displacements are reasonable in pattern and magnitude. *Thus the cavern is stable. It does not show any significant distress under this condition.*

Figure 3b shows contours of radial and tangential stress and Figure 3c shows contours of vertical and maximum principal stress for the same analysis step as Figure 3a. All components of normal stress are decreased for a radial distance of 500 to 600 ft away from the cavern wall. Tensile zones develop in the crown, sidewalls and floor of the chamber but all stresses are safely redistributed to areas hundreds of feet away from the cavern wall.

Once the chamber has been filled with cooled, compressed natural gas it may be maintained for some period of time to allow the surrounding rocks to approach steady state thermal equilibrium. One approach would be to close off the cavern containing a fixed volume of gas and wait. During this time heat flowing from the surrounding rock will warm up the gas in the chamber and cause the gas pressure to increase. Figures 4a, 4b and 4c show the temperatures, displacements and stresses 60 days after the chamber is filled (320 days total). Separate calculations by Vandor + Vandor were used to establish the gas temperature of -100º F and chamber pressure of 3,000 psi (2500 psig at ground surface) after 60 days at constant volume.

The size of the cooled zone of rock increases somewhat during these 60 days and the radial displacements increase a little. However, the stresses near the cavern wall become more compressive during this time and the size of the zone of tensile stresses decreases significantly. Apparently, what happens is that the increase in temperature and increase in chamber pressure causes sufficient expansion in the cavity walls to cause them to go into a compressive stress state again. The displacement patterns and magnitudes are reasonable and acceptable and the analysis remains numerically stable. *The cavern does not show significant distress during this time.*

Initial designs considered the possibility of emptying the chamber of gas in a minimum period of 10 days. Separate calculations by Vandor + Vandor indicated one scenario where gas pressure drops to 640 psi in the chamber (140 psig at ground surface) and gas temperature drops to -190º F. Figures 5a, 5b and 5c show the temperatures, displacements and stresses at the end of this 10 day period. The displacement and stress patterns are similar to those at the end of the initial cooling period. The sub-zero zone covers a larger volume. *The cavern remains stable.*

Initial designs considered a minimum refilling period of 20 days. Figures 6a, 6b and 6c show the temperatures, displacements and stresses at the end of this 20-day period. The displacement and stress patterns are similar to those at the end of the initial cooling period. Comparing maximum principal stress shown on Figure 6c with that on Figure 4c shows that the zone of tensile stresses is somewhat larger, probably because the cold zone has moved deeper into the rock. Stresses near the cavern wall have become more compressive than after first cooling. *The cavern remains stable.*

Evaluation of the Results

Three-dimensional analyses over time produce massive amounts of data that can be difficult to interpret. One useful way is to track stresses and displacements at a few representative points over time. Figures 7a, 7b and 7c show displacements of some points along a vertical line through the center of the chamber and a horizontal line radiating away from the chamber at mid-height. Figure 7a shows very little vertical movement at the crown and invert of the chamber during excavation. There is about 0.08 ft of heave of the crown and settlement of the invert during the first pressurization. During cool down, the crown settles another 0.1 ft and the invert heaves slightly. Vertical movements are small during the empty-fill cycles. Figure 7b shows vertical movements along a horizontal line radiating away from the mid-height of the chamber. There is no vertical movement along this line until cool down, during which about 0.1 ft of settlement occurs. Figure 7c shows horizontal movement of points along the same line. The chamber wall moves inward slightly during creation of the cavern. During cool down, it moves outward by as much as 0.5 ft. These radial displacements decrease to near zero about 150 ft away from the cavern wall. Beyond this point, displacements are actually inward towards the cavity due to contraction of the cooled rock around the cavern. Only slight movements occur during the empty-fill cycles.

Figures 8a, 8b and 8c show stresses along a horizontal line radiating away from the cavern at its mid-height. Except for the maintain phase where the gas pressure rises to 3,000 psi in the chamber, the radial stress along this line is less than the original geostatic stresses for all conditions and never goes positive. Cracking does not occur in the radial direction. The tangential stress increases during excavation of the cavern, which is the expected result due to stress relief within the cavern. The tangential stresses decrease during cool down sufficiently to create vertical tensile cracks in the radial direction for about 200 ft from the cavern wall. These cracks close and compressive tangential stresses develop during gas removal. The vertical stress remains essentially constant during excavation, which is the expected result for the modeled condition. It decreases near the cavern wall during cool down to the point that tensile stresses develop and the rock may crack along horizontal planes up to 200 feet away. These cracks close and compressive vertical stresses develop during gas removal.

These results show that the most critical time for cavern stability is during initial cooling when tensile stresses can cause cracking on vertical planes radiating away from the cavern wall. Faster cooling appears to cause more cracking. Slower cooling reduces cracking but presents cost disadvantages because it ties up valuable product for a longer time. Despite the cracking, the walls remain stable because the rock remains uncracked in the radial direction away from the chamber and stresses within the cracked zone are safely transferred to rock outside the tensile zone.

Advanced numerical analyses performed by us for this work show:

(1) A 150 ft diameter by 500 ft high chamber located at 3,000 ft deep remains stable through all phases of filling and emptying the chamber with cold compressed gas subject to the following limitations:
   a. Gas pressure cannot exceed 2500 psi at the crown of the chamber.
   b. Gas pressure should not fall below 400 psi at the crown of the chamber.
   c. Initial cool down requires several months to minimize thermal cracking. (The exact time will depend on specific geometry of the chamber, geologic conditions and pressure of the gas.)
   d. Conditions that produce more than 5 ft of liquid gas at the bottom of the chamber should be avoided.

(2) An eight-foot diameter by 500 ft chamber located at 3,000 ft deep remains stable through all phases of filling and emptying the chamber with cold compressed gas subject to the same limitations.

(3) A small diameter chamber with a height at least six times its diameter can suffice for a test chamber. Since the tensile stress condition during thermal cooling appears to worsen with decreasing chamber diameter, there is a limit to how small the chamber diameter may for the test to remain representative. Additional analyses should be performed for the actual Phase II test chamber to verify that its dimensions will give representative behavior.

(4) Differential slip between the dolomite roof and the underlying salt is acceptably small around the riser pipe as long as the pipe is near the center of the chamber roof.

(5) Small and large pieces of saltstone may fall from the roof and from the sides of the cavern during initial cooling and during operation as the rock outside the cavern contracts and expands. These localized rock falls do not threaten the overall stability of the cavern, nor its ability to contain the stored gas.

Cracks may develop along vertical planes radiating outward from the cavern walls for distances of 200 to 300 ft. However the analyses show that the cavern walls will remain stable and gas tight. Multiple wells would have to be spaced at distances of about 1,000 ft to minimize the risk of gas flowing from one chamber to another through these cracks.

These results show that the most critical time for cavern stability is during initial cooling when tensile stresses can cause cracking on vertical and horizontal planes radiating away from the cavern wall. Faster cooling appears to cause more cracking. Slower cooling reduces cracking but presents cost disadvantages because it ties up valuable product for a longer time. Despite the cracking, the cavern remains stable because the rock remains uncracked in the radial direction away from the chamber and vertical stresses within the cracked zone are safely transferred to rock outside the tensile zone.

These results show that it is safe to proceed with a field test to demonstrate that cold, compressed gas can be safely stored in an underground salt cavern with geologic conditions similar to those examined in this work. The specific field test conditions will depend on the geologic conditions at the test site. The field test may use a smaller diameter chamber and a shorter test length to reduce the volume of gas required for the test. Additional analyses should be performed for the field evaluation chamber to verify that its dimensions will give representative behavior. A field test using cold, compressed nitrogen will simulate most of the geomechanical effects of cold, compressed natural gas on the stability of the cavern. Should something go wrong or an unexpected event occur, the loss of nitrogen will produce no safety hazard at the ground surface. A small diameter cavern will not stress the roof rock as much as a larger diameter cavern, nor will it expose the chamber to large rocks falling from the cavern roof or walls that may occur during compression of the rock from freezing. Nevertheless a field test in a small diameter chamber with cold, compressed nitrogen is the logical next safe step towards developing the technology of storing cold, compressed natural gas in underground caverns.

Conclusions and Recommendations

Underground caverns made by solution mining of saltstone have been used for several decades to store crude oil and compressed natural gas at ambient temperatures. Large salt deposits make ideal storage facilities because they are essentially impermeable to the flow of liquid and gas and they have sufficient strength to remain stable for a wide range of conditions. Extensive geotechnical studies have also been made to store nuclear waste inside caverns mined in saltstone. A primary geotechnical consideration in the design of these facilities has been the high creep rate of saltstone under elevated temperatures that can cause the cavern to slowly close in on its self.

Very little geotechnical work reported in the literature has considered storage of cold, compressed gas at temperatures below -20º C in salt caverns. In our opinion, until the last few years the geotechnical profession's analytical and numerical capabilities were insufficient to examine the complex effects of low temperatures on the mechanical behavior of the cavern walls. The work described in this report shows that cold, compressed gas can be safely stored in underground salt caverns subject to some restrictions.

Laboratory tests performed on core samples of saltstone and dolomite from a site in western New York show:

(1) Fragments of saltstone and dolomite experienced no visible damage from immersing them in liquid nitrogen at -240º F.
(2) Compressive strength of saltstone and dolomite increased as temperature was decreased from room temperature to -150º F.
(3) Tensile strength of saltstone and dolomite increased as temperature was decreased from room temperature to -150º F.
(4) Stiffness of dolomite did not change significantly as temperature was decreased from room temperature to -150º F.

Advanced numerical analyses described herein show:

(1) A 150 ft diameter by 500 ft high chamber located at 3,000 ft deep remains stable through all phases of filling and emptying the chamber with cold compressed gas subject to the following limitations:
    a. Gas pressure cannot exceed 2500 psi at the crown of the chamber.
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    c. Initial cool down requires several months to minimize thermal cracking. (The exact time will depend on specific geometry of the chamber, geologic conditions and pressure of the gas.)
    d. Conditions that produce more than 5 ft of liquid gas at the bottom of the chamber should be avoided.
(2) Differential slip between the dolomite roof and the underlying salt is acceptably small around the riser pipe as long as the pipe is near the center of the chamber roof.

(3) Small and large pieces of saltstone may fall from the roof and from the sides of the cavern during initial cooling and during operation as the rock outside the cavern contracts and expands. These localized rock falls do not threaten the overall stability of the cavern, nor its ability to contain the stored gas.

(4) Cracks may develop along vertical planes radiating outward from the cavern walls for distances of 200 to 300 ft. However the cavern walls will remain stable and gas tight. This result indicates that multiple wells should be spaced at distances of about 1,000 ft to minimize the risk of gas flowing from one chamber to another through these cracks.

These results are specific to the geometry, material properties and loading conditions used in the analyses. A significant deviation of any of these conditions may cause substantially different results and change the conclusions. Since the effects of these factors involve a complex, coupled interaction of temperature, stress and displacement, a site specific analysis of actual conditions must be performed for each chamber under consideration for compressed cold gas storage.

These results show that it is safe to proceed with a field test to demonstrate that cold, compressed gas can be safely stored in an underground salt cavern with geologic conditions similar to those examined in this work. The specific field test conditions will depend on the geologic conditions at the test site.

A field test using cold, compressed nitrogen will simulate most of the geomechanical effects of cold, compressed natural gas on the stability of the cavern. Should something go wrong or an unexpected event occurs, the loss of nitrogen will produce no safety hazard at the ground surface. A small diameter cavern will not stress the roof rock as much as a larger diameter cavern, nor will it expose the chamber to large rocks falling from the cavern roof or walls that may occur during compression of the rock from freezing. Nevertheless a field test in a small diameter chamber with cold, compressed nitrogen is the logical next safe step towards developing the technology of storing cold, compressed natural gas in underground caverns. The field test may use a smaller diameter chamber and a shorter test length to reduce the volume of gas required for the test. The field test may be performed with the cavern partially fill with brine. NYSERDA has approved the funding for this field test.

Storing cold compressed gas in underground caverns presents an exciting opportunity to provide safe, economical storage and supply of natural gas. Historically such facilities were not developed because engineers did not have the analysis tools to adequately consider the effects of tensile stresses created by cooling on the overall stability of the cavern. They sought to avoid designs that caused significant tensile stresses in rock. Developments in the past ten years have provided very sophisticated analysis tools that allow detailed examination of the effects of pressurization and cooling on the complex behavior of geologic materials. Results from these analyses show us that the development of tensile stresses in the wall of a salt cavern due to cooling do not necessarily cause the cavern to collapse. Some deterioration of the cavern walls and roof may occur due to localized aspects of the rock and the cavern geometry; however this should not lead to a collapse of the cavern. Cavern stability can be safely maintained indefinitely in certain geologic formations by controlling the operating pressure and temperature of the stored contents.

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References

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[1] "Shear stress intensity" is used in this document as the ratio of the mobilized maximum shear stress at a point to the available shear strength at this point.

[2] RESPEC (2001). "Storage of chilled natural gas in bedded salt storage caverns." Report RSI-1354 to USDOE-NETL Pittsburgh, PA. November

[3] Rickard, L.V. (1969) "Stratigraphy of the Upper Silurian Salina Group – New York, Pennsylvania, Ohio, Ontario." Map and Chart Series Number 12, New York State Museum and Science Service. The University of the State of New York, Albany, NY.

[4] See Hoek and Brown (1980). *Underground Excavations in Rock*, E & FN Spoon Publishers, for more information.

[5] RESPEC (2001) op cit

[6] Jagla, E.A. (2003) "On maturation of crack patterns." The Abdus Salam International Centre for Theoretical Physics Strada Costiera 11, (34014) Trieste, Italy.

[7] Jagla, E.A. (2002) Phys. Rev. E 65, 046147