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679 Plank Road
Clifton Park, NY 12065, USA

Telephone: +1 518-579-6587
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Kelsey Wong, Student University of Texas Austin, Austin TX

Joel Warneke, Cavern Solutions, Houston, TX

Ed Beniot, Cavern Solutions, Houston, TX

Crystal Deroche, Cavern Solutions, Houston, TX

Dave Marchese, Caliche Development Partners, Houston, TX

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Kelsey Wong, Joel Warneke, Ed Beniot, Crystal Deroche and Dave Marchese
University of Texas, Austin, Cavern Solutions, and Caliche Development Partners

Abstract

Helium (He) is a chemically inert, low-density noble gas with unique physical properties that make it essential for a wide range of industrial, scientific, and medical applications. With the lowest boiling and melting points of any element, helium remains a gas under most conditions and only liquefies at extremely low temperatures. These properties make it indispensable for cryogenic cooling, superconducting magnets, semiconductor manufacturing, and aerospace systems.

Despite its importance, helium is relatively rare in the Earth's atmosphere, occurring at only about 5 parts per million. Commercial helium is primarily extracted from natural gas reservoirs where it has accumulated over millions of years. The limited global supply, combined with its non-renewable nature, makes helium a critical and strategic resource.

Large-scale storage of helium presents unique technical challenges. Its low molecular weight allows it to diffuse through many conventional storage materials, including metals, making containment difficult. High-pressure, leak-tight vessels and cryogenic conditions can mitigate losses, but these methods are limited in scale. Consequently, solution-mined salt caverns have emerged as one of the most effective means of storing helium. Salt caverns offer natural gas-tight containment, high-pressure tolerance, and flexibility for cyclic injections and withdrawal. However, maintaining purity and operational efficiency requires careful control of cavern pressure, temperature, and potential contaminants.

This paper presents a case study of the creation of the largest helium storage in a solution-mined salt cavern in North America, highlighting the integration of geological, drilling, and operational strategies to achieve high-purity storage while minimizing operational risk. The discussion focuses on wellbore design, mechanical integrity testing, cavern leaching methodology, and gas management practices that ensure safe and efficient helium storage.

Key words: Leaching, Workover, Drilling, Nitrogen, Helium, Conversion

Introduction

The Golden Triangle Storage (GTS) Well No. 5 is currently the largest helium cavern created in North America with a volume of 4.2 million barrels (667,745 m³). GTS Well No. 5 was spudded on the 18th of July 2023 and was placed into active storage service on the 7th of April 2025. The cavern was built for Caliche Development Partners II as part of the GTS lease. The GTS cavern facility is located in Jefferson County, Texas, at the Spindletop salt dome. The Spindletop field is known for its rich production history, beginning with the discovery of oil in 1901. The process of discovering the oil began with self-taught geologist Patillo Higgins, making a claim of Spindletop's geological makeup in 1890. Higgins proposed that, due to indications found on the surface of the field's mound, "there was oil under the Hill" and it should be explored (House, 1946). This led to Anthony Francis Lucas beginning drilling in 1900 with oil men Guffey and Galey along with oil well contractors, the Hamill brothers. Their efforts resulted in Spindletop's most notable achievement, the Lucas Gusher oil well where a geyser of oil shot “some 200 ft (61 m) into the air” and “poured an estimated 800,000 bbl (127,190 m^3) of oil onto the surrounding land” (Spindletop - a Texas Titan, 1945). This discovery paved the way for the newly competitive American oil business with “the next six gushers in the developing field [producing] more oil per day than the rest of the fields in the world added together” (McComb, 2021). Following the discovery of oil in Spindletop, the field was heavily produced and “was depleted and nearly abandoned by 1924” before new methods were employed to continue any further production (Lyle, 2000). With production dwindling, Spindletop began to be considered for other purposes, sulfur mining, brine mining and eventually salt cavern storage.

Spindletop’s extensive recorded history and known geological composition make it an ideal site for storage purposes. However, when designing a storage cavern, it is critical to understand and consider the complex geologic characteristics of the Spindletop salt dome. Due to the intense production of the Spindletop oil field and the production of sulfur from the domal caprock, extra caution must be taken when drilling a gas storage cavern. While the Spindletop salt dome was used for brine production since the 1950’s, its first gas storage cavern was not completed until 1992 with a volume of about “1.8 million bbl (286,177 m^3)” (Shotts, Randy, Solis, & Oldham, 1994). This led to the beginning of Spindletop’s usage as a gas storage cavern field which will eventually house many storage caverns, storing both liquid and gas products.

The repurposing of Spindletop for helium storage reflects both the strategic value of the site and the evolution of subsurface engineering practices. The GTS helium cavern leverages the field’s geomechanical integrity and containment properties to support high-purity, high-pressure gas storage in a secure and scalable configuration.

Site Selection and Drilling

Site selection for subsurface storage requires careful evaluation of salt dome geology, particularly structural complexity and overburden integrity. The Spindletop salt dome is classified as a shallow piercement-type structure, characterized by steep flanks, a relatively flat crest, and a diameter of approximately one mile. The dome extends to a depth of more than 8,000 feet (2,438 m), with the shallowest salt encountered at approximately 1,200 feet (366 m) below ground surface (Barton & Paxson, 1925). We now know with further exploration that the dome is still in contact with the base salt approximately 20,000 ft (6,096 m) depth.

Normal faulting is present throughout the formation; however, these faults are typically non-propagating and tend to self-heal over geologic time, posing minimal long-term risk to cavern integrity. The dome’s surface expression reaches a maximum elevation of 27 feet (8 m) above sea level and appears as a subtle circular mound (Eby & Halbouty, 1937). Its composition is consistent with other Gulf Coast salt domes, offering favorable conditions for solution mining and hydrocarbon storage.

Overlying the salt is a porous limestone caprock, historically targeted for oil production due to its high permeability and hydrocarbon saturation. Understanding the spatial relationship between the caprock, fault zones, and salt interface is critical for optimizing cavern placement and ensuring mechanical integrity throughout the cavern lifecycle.

While the historical record remains invaluable, figure 1 are images from google earth. What once was a hill on the Gulf Coast as described above is now an area that has been exploited for resources for more than 120 years. Special considerations and precautions need to be taken for site selection and during the drilling of a cavern well on the dome. Some of the considerations should include spacing of other caverns, distance to the salt flank, shoe depth for helium storage, formation gases, loss circulation zones at various horizons, and historic sulfur mining of the caprock to start the list.

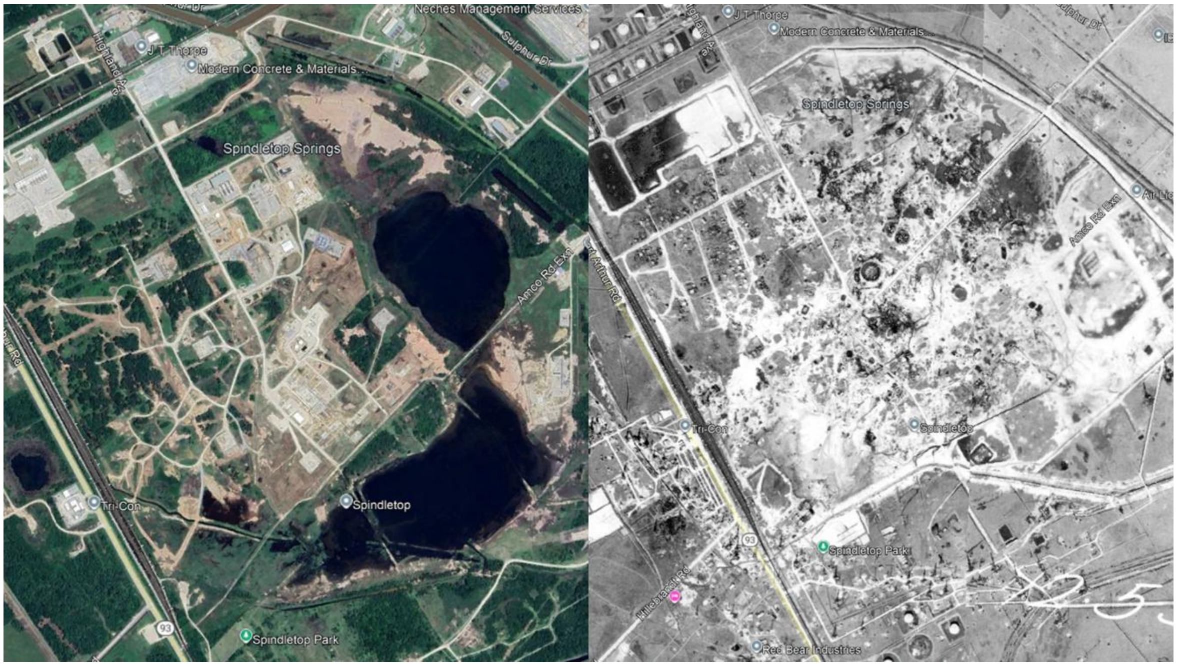


Figure 1 - Historical Images of Spindletop Salt Dome, Left is 2025 and Right is 1938

The historical reports along with modern data collection efforts on the salt dome laid the foundation to be able to design a cavern using the four principles that Ron Benefield has stated, “Size of the cavern, shape of the cavern, the span of the cavern, and the separation between neighboring caverns” (Benefield). Applying these parameters to the known geological information about Spindletop allowed for the site selection and initial design of the GTS No. 5 cavern.

Once the cavern design was finalized, project development advanced with drilling operations commencing in July 2023. Unlike other nearby locations on the dome, this well encountered relatively few complications during drilling. Typically, wells at Spindletop must contend with three known loss circulation zones and legacy impacts from historical Frasch-process sulfur mining. In this case, however, those challenges were minimal, allowing for a more streamlined execution of the drilling phase.

Summary of Drilling Operations for GTS No. 5

Drilling operations for the GTS No. 5 cavern began on July 18, 2023, following the installation of a 42-inch (1,067 mm) drive pipe to a depth of 215 feet (66 m). The surface hole was drilled to 1,000 feet (305 m), logged, and secured with 30-inch (762 mm) surface casing. The intermediate section advanced through the top of salt at 1,650 feet (503 m) and continued to 2,030 feet (619 m), where 24-inch (610 mm) intermediate casing was run and cemented at 2,020 feet (616 m).

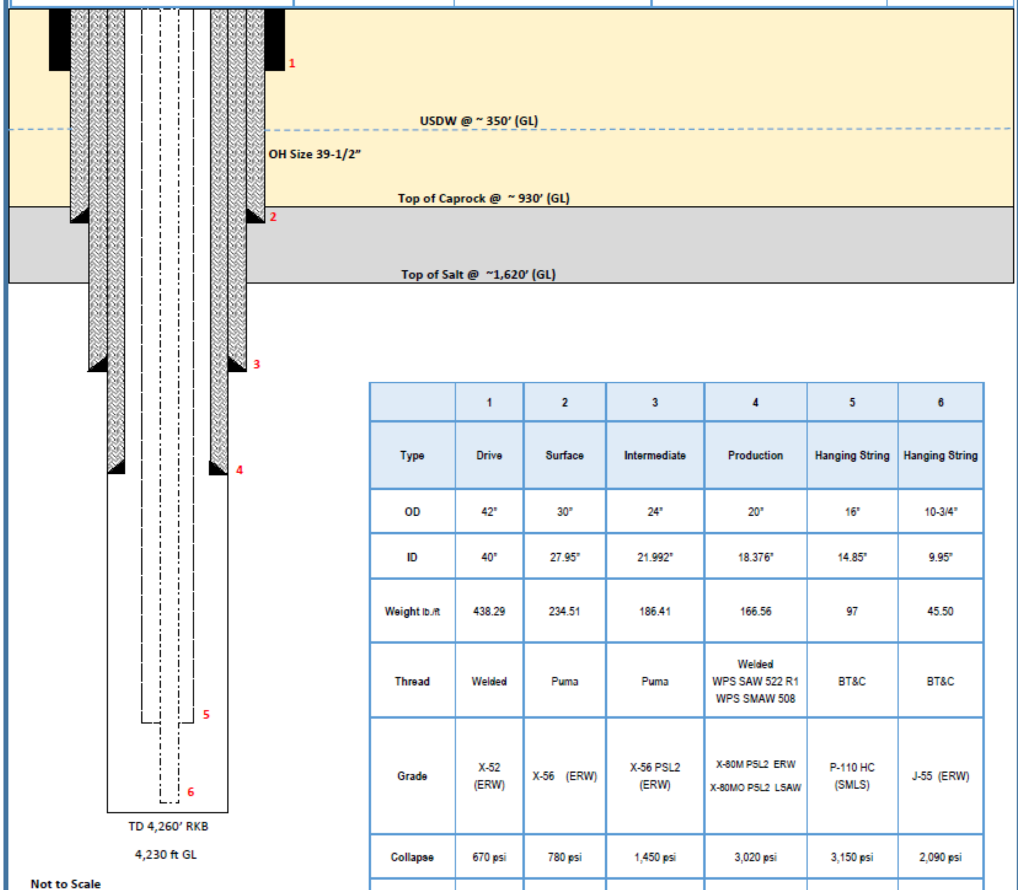
The salt section drilling proceeded to 2,425 feet (739 m), during which a 90-foot (27 m) core was collected in three 30-foot (9 m) intervals. The borehole was then enlarged using successive hole openers, followed by a caliper survey and installation of 20-inch (508 mm) production casing, which was cemented in place.

Drilling continued to a total depth of 4,255 feet (1,297 m), incorporating multiple underreaming stages, logging runs, and bottom-hole reaming to 4,225 feet (1,297 m). Final operations included running the hanging strings, after which the rig was released on October 6, 2023.

Overall, the drilling phase progressed smoothly and without major complications, successfully preparing the well for subsequent cavern development and subsequent storage operations.

Figure 2 is the wellbore schematic post drilling.

Caliche Golden Triangle Storage		GTS Cavern No. 5		
Field: Spindletop	**County:** Jefferson	**API:** 42-245-32907	**Top of Cap Rock:** ~930' GL	
State: Texas	**Sonar Date:**	**UIC No.:** 366287	**Top of Salt:** ~ 1,620' GL	
Lease: Golden Triangle Storage	**Spud:** 07/18/2023	**Serial No.:** 100949	**Cavern Volume:**	



	1	2	3	4	5	6
Type	Drive	Surface	Intermediate	Production	Hanging String	Hanging String
OD	42"	30"	24"	20"	16"	10-3/4"
ID	40"	27.95"	21.992"	18.376"	14.85"	9.95"
Weight lb./ft	438.29	234.51	186.41	166.56	97	45.50
Thread	Welded	Puma	Puma	Welded WPS SAW 522 R1 WPS SMAW 508	BT&C	BT&C
Grade	X-52 (ERW)	X-56 (ERW)	X-56 PSL2 (ERW)	X-80M PSL2 ERW X-80MO PSL2 LSAW	P-110 HC (SMLS)	J-55 (ERW)
Collapse	670 psi	780 psi	1,450 psi	3,020 psi	3,150 psi	2,090 psi
Depth GL	~215'	~970'	~1,988'	~2,347'	~3,450'	~4,210'
Depth RKB		~1,000'	~2,018'	~2,377'		
Coating			Depth 1,606-1688 ft (Joints 8 & 9) sand blasted. 3 coat carboline epoxy. Top Coat Yellow (OES)	Joints 1 and 2 (Bottom 80 feet) externally sand blasted		
Cement	Driven	Lead 3389 sxs 12.0 ppg slurry + Tail 1945 sxs 14.5 ppg slurry Type 1L & add.	Tail 2356 sxs 16.10 ppg slurry Class H + add. Top Out w 200 sxs 15.6 ppg Type 1L & add.	Lead 1175 sxs 16.10 ppg slurry Class H HSR (1,962')+ Tail 535 sxs 16.10 ppg slurry Class H HSR & Latex (335')+ Neat Resin 20 bbls 18.23 ppg (50')	NA	NA

Figure 2 - Cavern No. 5 Well Bore Diagram

Pre-MIT and Leaching Considerations

A recommended procedure following drilling is to perform a mechanical integrity test (MIT). For this particular well, it was necessary for each stage of the work to demonstrate integrity. This approach has been referenced in various SMRI papers and API recommended practices (RP 1115 and 1170). The primary considerations focus on identifying any issues after drilling and before leaching.

If wellbore integrity problems are found at this phase, they can be addressed more efficiently and cost-effectively before leaching begins. Additionally, conducting a pre-MIT establishes a record that the well and wellbore were completed with integrity at a specific time. During leaching, fluid flow and stress changes occur due to salt mining, which may affect the wellbore. By confirming wellbore integrity prior to leaching, information from before and after leaching can be compared. The paper will address both pre-MIT and post-leaching MIT in later sections.

The 2017 SMRI technical class, "Well Integrity Management for Salt Caverns," featured a session led by Dr. Warneke and Ron Benefield, entitled "Well Integrity Considerations During Solution Mining and Completion." This session explored gas cavern development philosophy that contrasts with several traditional cavern developments. This cavern and others developed by Dr. Warneke and Mr. Benefield show that the development philosophy from that class not only works but allows the cavern to be leached more efficiently and cost effectively.

The main points for the gas cavern development philosophy are:

- Determine the need for intermediate service,
- Develop a desirable cavern and roof shape,
- Minimize Down Time (It's all about production),
- No Workovers (if possible),
- Completely develop the lower cavern, first,
- Then develop the upper cavern and roof,
- Use an N2 blanket where feasible.

After many discussions with the customer the goal for the cavern was to create the largest Helium storage cavern in the world and to have the leaching of the cavern done in approximately 12 months. Since this is a very specific product there was no need to design the cavern for intermediate service. We still had a timeline of development which meant that if leaching goals were not achieved, then the cavern would not reach the desired size in the time allotted for leaching.

The leaching simulation for the cavern was run on both Salgas and SANSMIC. The leaching simulation goals were two-fold, 1) where do we place the hanging strings such that no major workovers must be completed while obtaining an optimal storage shape and 2) develop saturation tables to allow for the tracking of not only the production/space creation but help with the designing of the nitrogen pad. The initial leaching string settings can be found in the wellbore schematic, Figure 2 above.

Given the sensitivity of delivering a high-purity product, the customer opted to utilize a nitrogen pad during cavern development. This approach eliminated concerns about hydrocarbon contamination and supported the natural formation of an arched roof at the conclusion of the leaching process.

Historically, the use of nitrogen pads has presented challenges, including uncertainty about pad placement and compression behavior. These issues occasionally require additional wireline logging and other diagnostic efforts to verify that the nitrogen pad is positioned correctly and performing as intended.

To address these concerns, Cavern Solutions has implemented a series of measures over the years to enhance reliability and pad performance. Key practices to ensure the nitrogen pad effectively limits upward cavern growth include:

- Pre-leaching Mechanical Integrity Testing (MIT): Confirms gas-tight integrity of the system before leaching begins.

- Gas-tight couplings in outer hanging strings: Prevents unintended gas migration and maintains pad containment.
- Proper instrumentation of the wellhead and flow manifold: Enables accurate monitoring of pad pressure and system behavior throughout operations.

For this and other projects, the Nitrogen-Brine Interface is calculated in real-time by incorporation of the initial Nitrogen Charge Volume with dynamic variables including friction losses for both Injection and Return Flow Rates, Nitrogen Surface Pressure, Injection Pressure, and Brine Return Pressure, all of which are adjusted for temperature. All calculations are based off surface instrumentation, and no additional wellbore or downhole instrumentation is required.

The result is a high-purity, low-contamination storage cavern with a naturally domed roof. Additional benefits are reduced pad material and disposal costs, low environmental impacts, faster mechanical integrity test ready at conclusion of solution mining depending on temperature and end of cycle saturation, and lower cost workovers. This solution is also applicable utilizing other compressible, low hazard fluids such as helium, argon, etc. Compensation for compressibility is accomplished by utilizing highly accurate and reliable industry-standard equations for determining downhole pressures, hydraulic effects, and other system behaviors.

The main drawback to this process is the limited range of flow rate deviation, as higher or lower flow rates will move the interface up or down, and potentially out of the desired range for the final roof. If rate changes are operationally required, then adjustments to the initial charge volume can re-establish the roof development at the desired depth based on the new operational flow rate and flow rate range. This process also requires continuous monitoring, at a minimum, daily to identify potential issues early.

Figure 3 shows the cavern at the end of sump building.

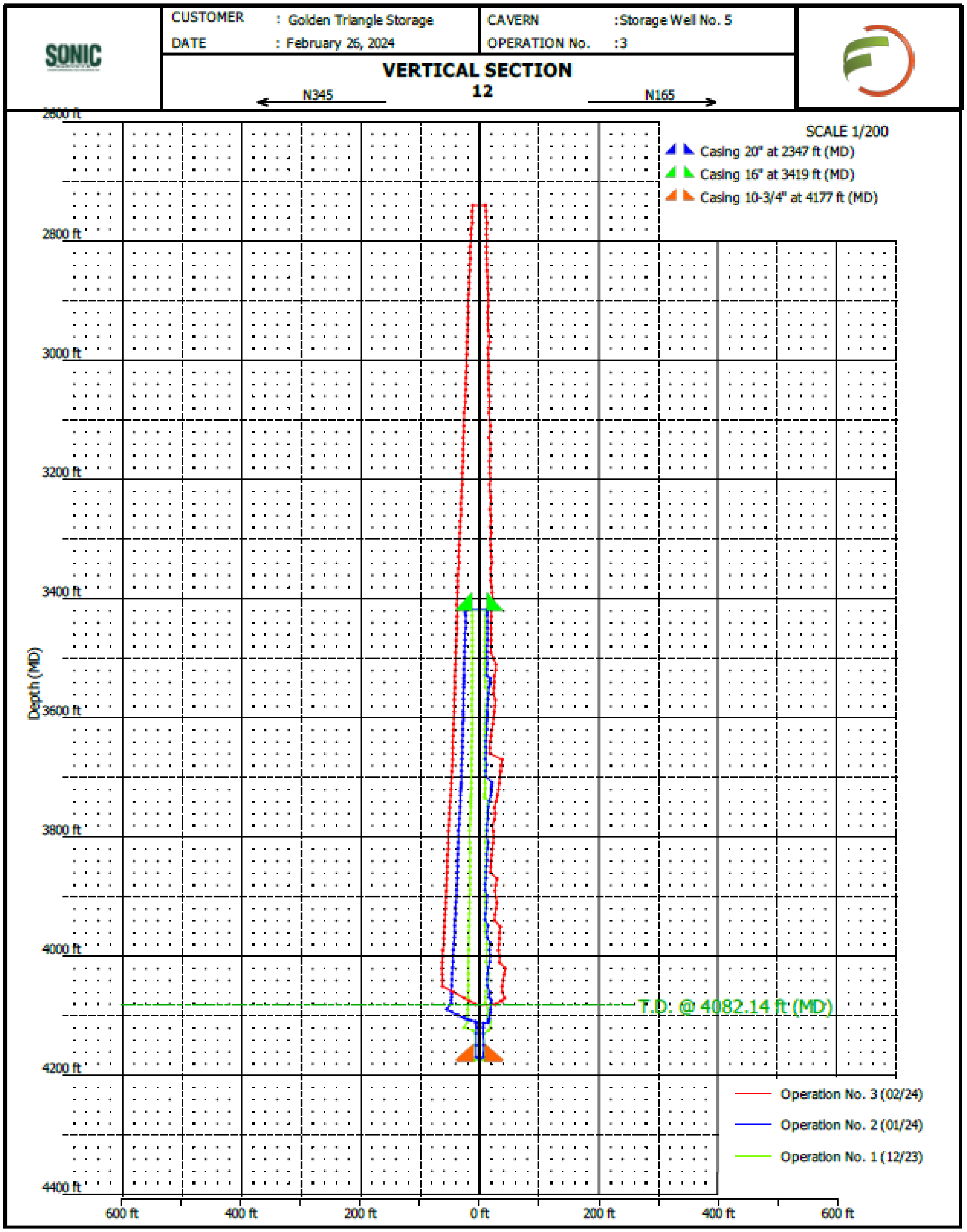


Figure 3 - Cavern No. 5 Direct Leaching Finished

After the cutting of the inner hanging string the cavern production was conducted with reverse mining. The water was injected through the outer hanging string, and the brine was withdrawn from the cavern through the inner hanging string. This mining method is where the true cavern space is created due to higher mining efficiency from reverse mining.

Figure 4 shows the cavern after leaching was completed.

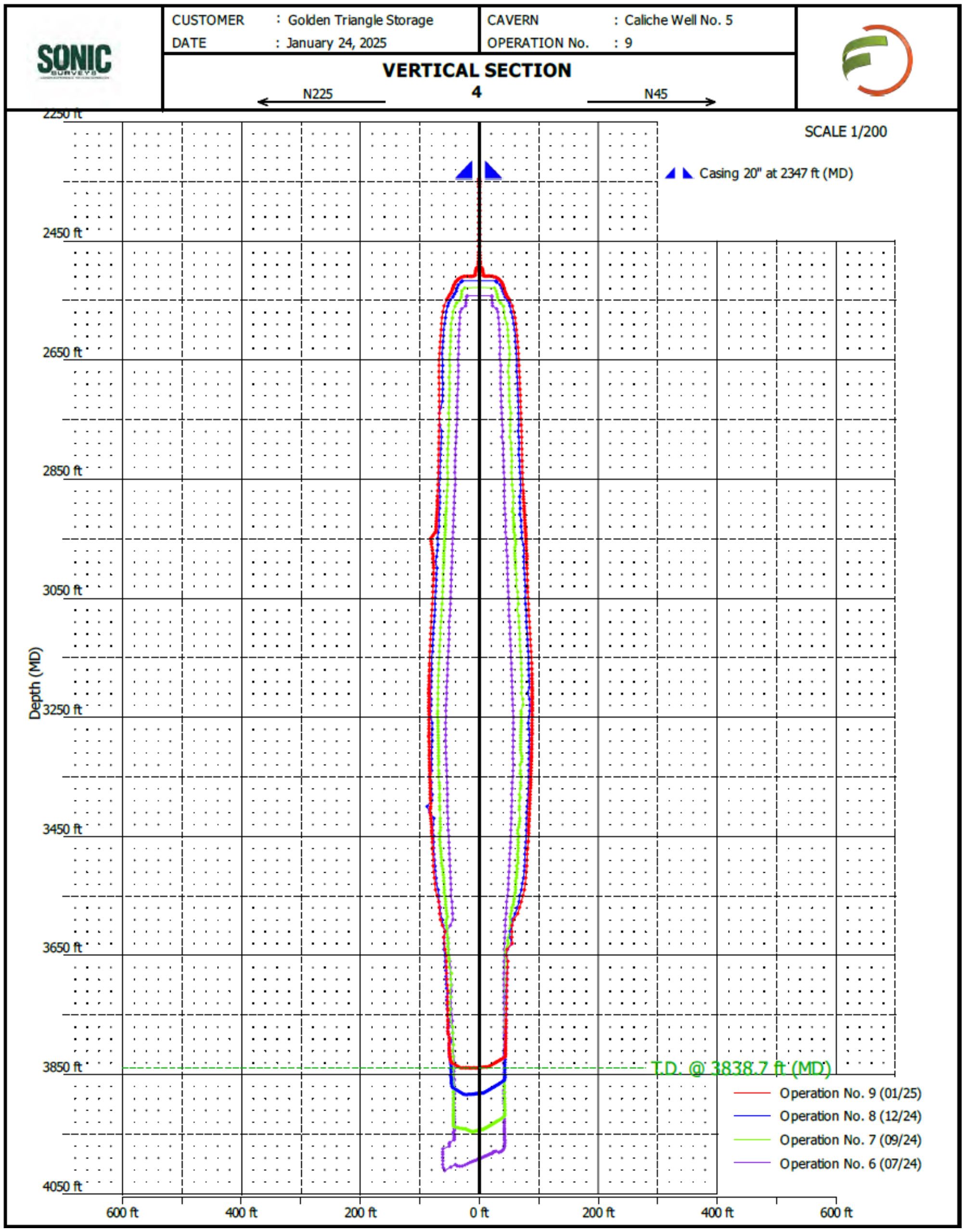


Figure 4 - Cavern No. 5 Leaching Completed

Looking closer at the sonar you can see the benefit of using a nitrogen pad. As the saturation of the cavern increases, the pressure exerted on the nitrogen pad increases, compressing the pad and naturally arching the roof.

During the leaching of the caverns there was zero down time due to operations involving the cavern. This includes sonar surveys, hanging string movements, and mining method changes. By properly configuring the hanging strings and pre-planning operations, these tasks were completed while the well was flowing, which saved approximately 30 days on the leaching timeline. This approach also avoided the costs associated with workovers, interface logging, and non-flow logging activities.

Figure 5 shows the calculated pad movement during the leaching process.

Figure 5 - Nitrogen Pad Monitoring During Leaching

Cavern Conversion

While the conversion of the cavern from leaching to storage may look like a traditional cavern conversion, there are several key differences that will be pointed out in the workover summary. Due to the intellectual property concerns of this conversion, some of the key details of the process must be left out of the paper, however the major steps are summarized below.

Summary of Well No. 5 Operations (January – April 2025)

Phase one: Removal of Nitrogen Leaching Pad and Machining of Bradenhead

Site Preparation and Rig Mobilization

The rig crew arrived on-site and prepared the location by moving rig equipment, laying mats, and spotting mud pumps and rig tanks. The derrick was rigged up, and pressures were checked. Nitrogen was bled off the well to prepare for casing operations.

Casing Operations

- **10-3/4” (272 mm) Casing:** Pulled and laid down successfully.
- **16” (406 mm) Casing:** Laid down and prepared for casing scraper operations.
- **20” (508 mm) Casing:** Casing scraper run to 2,320 feet (707 m).

Inspection and Wireline Logging

Wireline trucks operated by Baker Hughes and Sonic Surveys were used to run inspection logs, sonar caliper surveys, density tools, and pipe-thickness detection tools. Inflatable packers were set and retrieved for well testing.

Bradenhead and Wellhead Installation

- Braden head flanges and 20-inch (508 mm) mandrel hangers were machined and installed per specifications.
- Product spools were installed and torqued; wellhead equipment rigged down and moved off location.
- Quality control inspections were conducted on casing boxes and pins.

Rig Remobilization

- Workover Rig mobilized with support equipment, mats, forklifts, and light towers.
- Brine pressure bled off Cavern #5, fresh water spotted down 20-inch (508 mm) casing, and inflatable packers set at 998 feet (304 m).
- Tubing and packer pressure monitored.

8-5/8” (219 mm) Casing Welding Operations

- Welded L80 HC casing.
- Connections inspected with phased array after each weld and filled with brine.
- Casing hanger landed.

The multi-phase workover on the cavern was successful and the program moved to the final phase,

Mechanical Integrity Testing

As alluded to above there were two MIT’s conducted on this cavern during the project. The first MIT was the post drilling MIT and is important for several reasons regarding this project. First is that the MIT demonstrated that the wellbore, hanging strings, and wellhead equipment tested tight. The second reason is that the nitrogen that was used for the pre-MIT would be the nitrogen blanket used for leaching. It was imperative at this juncture that all the calculations that would be used to monitor the nitrogen pad for the leaching of the cavern be verified during the nitrogen injection. During the injection the metering, pressure, and temperature were closely watched and stopped at several intervals to ensure that what was predicted by our calculations is what was being witnessed downhole. The nitrogen pad was injected to a deeper depth than a normal MIT as this extra nitrogen is what would be used to create the cavern roof and ensure that the cavern neck was sufficient length.

In the end the wellbore tested the following results:

> Calculated Leak Rate (CLR) was -132.39 bbls/year (-21.05 m^3/yr) and the Minimum Detectable Leak Rate (MDLR) of 47.51 bbls/yr (7.55 m^3/yr). The pressure gradient for this test was 0.79 psi/ft (17,878.9 Pa/m) at the casing shoe.

The final MIT was intentionally extended to enhance resolution and confirm system tightness, as specified in the initial project requirements. The primary challenge in obtaining an accurate test result was stabilizing the wellbore. Extensive historical sulfur mining via the Frasch method altered the thermal profile of the caprock, resulting in a non-standard temperature gradient. A localized hotspot within the caprock required additional time for nitrogen stabilization prior to testing.

Once the nitrogen was stabilized, the test was conducted as a traditional nitrogen/brine MIT with the following results: a Calculated Leak Rate (CLR) of -13.19 bbls/yr (-2.10 m^3/yr) and a Minimum Detectable Leak Rate (MDLR) of 55.05 bbls/yr (8.75 m^3/yr).

Discussion

The development of the Golden Triangle Storage Well No. 5 represents a significant advancement in large-scale helium storage in solution-mined salt caverns. This case study demonstrates that careful integration of geological data, historical site knowledge, and advanced cavern design principles can result in the successful creation of a high-purity, operationally efficient storage facility.

Site selection at the Spindletop salt dome was critical due to the dome's complex history of hydrocarbon and sulfur production. Despite potential challenges from prior mining and faulting, the application of Benefield's four-principal design framework—considering cavern size, shape, span, and spacing—ensured both structural stability and operational flexibility. The shallow piercement type salt dome, with a relatively flat top and steep sides, provided a favorable environment for achieving the large cavern volume required for helium storage while minimizing the risk of interaction with neighboring caverns or compromised salt quality.

Drilling operations proceeded smoothly, aided by thorough pre-drilling studies and historical data, allowing for efficient wellbore construction with minimal complications. Mechanical integrity testing (MIT) conducted post-drilling, and post-leaching confirmed the robustness of the wellbore and wellhead equipment, validating the effectiveness of pre-leaching design and nitrogen pad methodologies. The use of a nitrogen pad proved particularly beneficial in controlling roof arching, maintaining helium purity, and reducing operational downtime, demonstrating the advantages of pre-planned interface management and continuous real-time monitoring.

Leaching operations benefited from reverse mining techniques and careful hanging string placement, which enhanced cavern creation efficiency. The ability to perform sonar, hanging string adjustments, and mining method changes without halting operations shortened the overall leaching timeline by approximately 30 days, demonstrating both operational and economic advantages. Additionally, the nitrogen-brine interface management minimized potential contamination and environmental impacts, further supporting the suitability of solution-mined salt caverns for high-purity helium storage.

Overall, this project underscores the importance of integrating historical site knowledge, precise engineering, and advanced operational strategies to achieve large-scale, high-purity helium storage. The techniques employed at GTS No. 5 can serve as a model for future helium or other light-gas storage projects in similar geological settings.

Conclusions

1. **Successful Creation of the Largest Helium Cavern in North America:** GTS Well No. 5 demonstrates that solution-mined salt caverns can be designed and executed to store helium at unprecedented volumes while maintaining high purity and structural integrity.

2. **Critical Role of Geological and Historical Data:** The comprehensive understanding of Spindletop's salt dome geology, including prior hydrocarbon and sulfur extraction, was key to site selection, well design, and leaching strategy, ensuring safe and efficient cavern development.

3. **Operational Efficiency Through Advanced Design:** Application of Benefield's cavern design principles, coupled with the nitrogen pad methodology and reverse mining, allowed continuous operations during leaching, reducing downtime and minimizing the need for costly workovers.

4. **Mechanical Integrity Verification:** Dual mechanical integrity tests—post-drilling and post-leaching—confirmed wellbore tightness and the effectiveness of operational protocols, supporting long-term operational safety and helium containment.

5. **Scalable Approach for Future Projects:** The strategies developed for GTS No. 5, including precise interface management, real-time monitoring, and staged cavern development, provide a replicable framework for future high-purity helium or other light-gas storage projects in similar salt dome environments.

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