

Design and Operation of Solution-mined Salt Caverns Used for Liquid Hydrocarbon Storage

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Design and Operation of Solution-mined Salt Caverns Used for Liquid Hydrocarbon Storage

1 Scope

This recommended practice (RP) provides the functional recommendations for salt cavern facilities used for liquid hydrocarbon storage service and covers facility geomechanical assessments, cavern well design and drilling, and solution mining techniques and operations, including monitoring and maintenance practices. This RP is based on the accumulated knowledge and experience of geologists, engineers, and other personnel in the liquid hydrocarbon storage industry and promotes public safety by providing a set of industry accepted design and operation guidelines. This RP recognizes the nature of subsurface geological diversity and stresses the need for in-depth, site-specific geomechanical assessments, with a goal of long-term facility integrity and safety.

This RP includes the cavern well system (wellhead, wellbore, and cavern) from the emergency shutdown (ESD) valve to the cavern and facilities that have a significant impact on the safety and integrity of the cavern system. It also includes a structure for risk assessment for salt cavern facilities used for liquid hydrocarbon storage service.

This RP may be applied to existing facilities at the discretion of the user.

This RP does not apply to caverns used for the storage of gaseous products, natural gas, brine production, or waste disposal, nor to caverns that are mechanically mined, or depleted hydrocarbon or aquifer underground gas storage systems. This RP does not cover facility piping.

1.1 Overview

Storage of liquid hydrocarbons in solution-mined salt caverns has been utilized in the United States since the late 1940s. Today, storage of liquid hydrocarbons in caverns developed in both domal and bedded salt formations is utilized throughout the world.

Salt caverns can act as long-term, seasonal storage vessels; or they may serve as short-term, operational storage. Caverns can also be inserted into the production plant/pipeline systems to prevent supply interruptions when maintenance or emergency shutdowns occur, or to “float” on pipelines to optimize operations.

Storage of liquid hydrocarbons in a salt cavern may require careful review to ensure that the product is compatible with the salt. Chemical and physical properties of the salt at the cavern depth and at the pressure anticipated should be reviewed to verify that unwanted chemical or physical reactions do not occur. Incompatibility of product and salt is rarely a problem for most hydrocarbons. Examples of exceptions are storage in salt caverns where sulfides are present and storage of jet fuels with de-icing agents that absorb water.

In summary, storage of liquid hydrocarbons in salt caverns can provide an economical, safe, and environmentally sound method to store large quantities of compatible materials.

1.2 Applicable Rules and Regulations

This document was written to provide a technical reference for the development and operations of solution-mined salt caverns used for the storage of liquid hydrocarbons, and is not intended to represent or reflect any regulatory requirement. Depending on location and nature of the project, the recommended practices herein may address items that are in conflict with some regulatory requirements. If this occurs, the regulatory requirement supersedes the recommended practice unless an appropriate waiver or variance is granted from the issuing agency. A thorough review of the applicable rules and regulations is to be performed prior to the design of solution-mined liquid storage caverns to ensure ongoing compliance.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Technical Report 5C3/ISO 10400:2007, *Technical Report on Equations and Calculations for Casing, Tubing, and Line Pipe Used as Casing or Tubing; and Performance Properties Tables for Casing and Tubing*

API Specification 10A, *Cements and Materials for Well Cementing*

ASTM D3967¹, *Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens*

ASTM D4543, *Standard Practices for Preparing Rock Core as Cylindrical Test Specimens and Verifying Conformance to Dimensional and Shape Tolerances*

ASTM D4645, *Standard Test Method for Determination of In-Situ Stress in Rock Using Hydraulic Fracturing Method*

ASTM D7012, *Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens Under Varying States of Stress and Temperatures*

ASTM D7070, *Standard Test Methods for Creep of Rock Core Under Constant Stress and Temperature*

3 Terms, Definitions, Acronyms, and Abbreviations

3.1 Terms and Definitions

For the purposes of this document, the following definitions apply.

3.1.1

annulus

The space between two lengths or strings of concentric pipe, or between a pipe and borehole.

3.1.2

attic

trap

An area in the cavern roof that could trap product.

3.1.3

backwash

The process of pumping fresh water into the brine string to remove salt buildup that can occur during product injection and brine withdrawal.

3.1.4

bedded salt

A salt formation in which the original depositional structure of alternating salt and non-salt beds is largely preserved.

3.1.5

blanket material

A fluid less dense than water and incapable of dissolving salt that is used during solution mining to protect the cavern roof from the injected water and prevent dissolving the salt of the roof and around the casing seat.

¹ American Society for Testing and Materials, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, Pennsylvania 19428-2959, www.astm.org.

3.1.6 borehole wellbore

A shaft bored or drilled into the ground at any angle between vertical and horizontal.

3.1.7 bradenhead casinghead starting head

A wellhead component typically attached to the intermediate casing and from which the blowout preventers (BOPs) are affixed during drilling and the remainder of the wellhead components are affixed after drilling.

3.1.8 brine

A solution of water and a variable amount of salt, generally sodium chloride, produced during solution mining and used for product displacement.

3.1.9 brine pond

The excavated or diked structure used for the surface containment of brine used in the creation, maintenance, and operation of an underground hydrocarbon storage cavern.

3.1.10 brine string

The uncemented tubing through which highly saline water flows into or out of a liquid hydrocarbon storage cavern during product withdrawal or injection operations.

3.1.11 caprock

Anhydrite, gypsum, and calcite cap above many salt formations that is formed by consolidation, cementation, and alteration of insoluble residue left by salt dissolution.

3.1.12 casing

Any of a number of sizes and lengths or strings of steel pipe, placed in the borehole to support the sides of the borehole, prevent uncontrolled movement of fluids into or out of the borehole or annular space, and allow production into and out of the well.

3.1.13 casing, conductor

Relatively short length of large diameter steel pipe used to prevent the borehole from caving during the initial drilling of a well.

3.1.14 casing, intermediate

One or more strings of steel pipe placed in the borehole inside the surface casing as needed to support the section of the borehole beneath the surface casing and to seal off intermediate water or hydrocarbon zones.

3.1.15 casing, liner

Casing placed in the borehole that does not extend the length of the well and is hung from the bottom of the previous casing string.

3.1.16 casing, production

The last cemented string of casing placed in the borehole inside the intermediate casing; used to flow into and out of the well.

3.1.17**casing seat**

The location or position of the bottom or lowermost position of a casing.

3.1.18**casing shoe**

A piece of equipment threaded or welded onto the bottom joint of a casing to facilitate the lowering of the casing into the borehole.

3.1.19**casing, surface**

Steel pipe placed inside the conductor casing in the borehole to protect underground sources of drinking water and other shallow geologic formations.

3.1.20**cavern**

An underground cavity developed by the solution mining of a salt formation.

3.1.21**cavern chimney**

The initial section of the cavern in early development that becomes the main cavern interval during the solution mining process.

3.1.22**cavern field**

A group of caverns within a salt dome or bedded salt formation.

3.1.23**cavern neck****uncased borehole**

A section of the borehole beginning directly beneath the casing seat and ending at the cavern roof. The neck is left uncased and is virgin borehole or minimally washed borehole.

3.1.24**cavern roof**

The uppermost part of the cavern located just below the neck of the wellbore. The shape of a salt cavern roof may be flat or domed.

3.1.25**cavern system**

The cavern, wellbore, casings, and wellhead.

3.1.26**cementing**

The operation in which a cement slurry is pumped down the inside of the innermost casing, out the bottom of the casing, and upward into the annular space behind the casing and the borehole or the previous casing.

3.1.27**circulation, direct**

The pumping of raw water down the center and longer hanging string, into the cavern, and returning brine to the surface through an outer and shorter string annulus.

3.1.28**circulation, reverse**

The pumping of raw water down an outer and shorter string annulus, into the cavern, and returning brine to the surface through the center and longer hanging string.

3.1.29**collapse pressure**

Pressure that, when applied to the exterior of a casing or tubing, causes it to collapse or fail.

3.1.30**core**

A cylindrical sample of geologic formation, usually reservoir rock, taken during or after drilling a well. Cores can be full-diameter cores (typically 4 in. in diameter) taken during drilling, or sidewall cores (generally less than 1 in. in diameter) taken after a hole has been drilled.

3.1.31**core, slabbed**

A core that is cut parallel to the core axis for analysis of grain structure.

3.1.32**creep**

The property of salt to flow slowly and deform permanently under the influence of shear stress.

3.1.33**creep closure**

The reduction in size of a cavern due to the natural flow of salt under lithostatic, tectonic, or overburden pressures.

3.1.34**dilution string**

A small-diameter hanging string installed inside the innermost brine string. The dilution string is used to inject fresh water into the brine string at one or more locations to remove or prevent the formation of salt buildup in the brine string.

3.1.35**domal salt****salt dome**

A mound or column of salt resulting from upward flow of a salt formation into shallower rock, and caused by the low density of salt relative to most sedimentary rocks.

3.1.36**dry drilling**

Drilling without significant fluid returns to the mud system at the surface.

3.1.37**emergency shutdown valve**

An automated valve designed to stop the flow of liquid upon detection of specific events.

3.1.38**fire detector**

A device capable of detecting the presence of a flame or heat from a fire.

3.1.39**formation**

A body of rock forming a separate and identifiable geological unit based on the rock characteristics.

3.1.40**hanging string**

A string of steel casing that is hung from the wellhead and inside the production casing and is not cemented. A casing whose weight is supported at the wellhead and hangs vertically in a larger cemented casing or another larger hanging string.

3.1.41**hole section**

A section of the overall cavern well borehole.

3.1.42**hydraulic communication**

The movement of fluid by a number of methods, including through porous or permeable rock, manmade conduits in the salt, annular movement, or casing leaks.

3.1.43**in-service date**

The date a newly constructed cavern system is available for liquid injections and withdrawals.

3.1.44**insolubles**

Minerals that do not readily dissolve in water.

3.1.45**interface**

A surface formed by the contact between two immiscible fluids in a well or cavern.

3.1.46**leak detector**

A device capable of detecting by chemical or physical means the presence of hydrocarbon vapor or liquid, or the escape of vapor through a small opening.

3.1.47**lithology**

The physical characteristics of a rock formation.

3.1.48**log**

A recording of a variety of subsurface properties made by lowering detectors into the well or cavern.

3.1.49**mechanical integrity test (MIT)**

A procedure that verifies a cavern system is capable of storing liquid hydrocarbons within design limitations with no significant loss of liquid.

3.1.50**maximum allowable operating pressure (MAOP)**

The maximum pressure authorized and measured at the product side of the wellhead.

3.1.51**microfractures**

Small fractures at a microscopic level.

3.1.52**mixing string**

A mixing string is a hanging string installed between the production casing and the brine string. The portion of the mixing string that extends into the cavern interval is typically perforated or slotted. Product injections are done through the mixing string and brine string annulus, which allows some mixing/blending of variable density product to be done in the cavern interval. Product withdrawals are done through the production casing and mixing string annulus.

3.1.53**non-aqueous drilling fluid**

A drilling fluid whose base fluid is not water.

3.1.54**overburden**

Geologic strata above the top of the salt deposit.

3.1.55**p-seals**

Wellhead-to-casing sealing mechanisms installed into the bore of wellhead components allowing for bands to be energized against the casing by the injection of packing material.

3.1.56**pillar****web**

A salt mass separating caverns and providing structural support to the cavern field.

3.1.57**plugged and abandoned well**

A well whose use has been permanently discontinued and filled with material and cement.

3.1.58**pressure gradient**

The pressure at a given depth divided by the depth.

3.1.59**pressure gradient, fracture****fracture gradient**

The pressure gradient that initiates fracture in the rock at the surface of a wellbore.

3.1.60**pressure gradient, operating**

The pressure gradient in the cavern system during normal cavern operation.

3.1.61**product**

Liquid or liquefied hydrocarbons, including crude oil and its products, its derivatives, or its byproducts of oil and gas that are as follows:

- a) liquid under standard conditions of temperature and pressure; or
- b) liquefied under the temperatures and pressure at which they are stored; and
- c) stored under conditions that necessitate the use of displacement fluids to withdraw them from storage.

3.1.62**radius of influence**

The distance a cavern significantly changes the initial, in-situ state of stress in the salt.

3.1.63**rock salt**

Rock composed of halite (sodium chloride) and minor concentrations of other minerals that form a crystalline or granular aggregate.

3.1.64**rubble, core**

A core that is crushed during coring.

3.1.65**rubble, floor**

Collapsed, nonsoluble beds and/or salt within the salt structure having fallen to the floor of the cavern.

3.1.66**safety strings**

The concentric pipe string placed between the brine string and the product string/casing.

3.1.67**salt stock**

The columnar body of a salt dome.

3.1.68**saltback**

The distance from the top of the salt to the casing seat.

3.1.69**solution mining**

The process of dissolving salt by means of circulating raw water from the surface, through a well to the subsurface where the salt is dissolved, and returning the fluid to the surface as brine.

3.1.70**sonar survey**

Measurement of the internal dimensions of a cavern using an acoustic wave generating/receiving tool.

3.1.71**subsidence**

Ground movement resulting from geomechanical phenomena, including the gradual salt creep closure of underground solution-mined caverns.

3.1.72**subsidence survey**

The periodic precision level survey of wellheads and strategically placed surface monuments at an underground storage facility to determine the rate of surface subsidence.

3.1.73**sump**

The lower section of a cavern developed to allow for the settling of insolubles embedded in the salt structure and released during solution mining.

3.1.74**tectonic salt**

A salt deposit that has been severely deformed by tectonic forces.

3.1.75**total cavern capacity**

The total cavern volume as determined by a sonar survey.

3.1.76**total liquid hydrocarbon storage capacity**

The maximum amount of liquid hydrocarbon that can be stored in the cavern in accordance with its design and operating procedures.

3.1.77**tubing**

Smaller diameter steel pipe(s) inserted in the production casing and used during solution mining for water or brine flow and during product filling for brine removal.

3.1.78**turn**

Injection and withdrawal of the entire working liquid capacity.

3.1.79**water**

Untreated surface or ground water, ranging in salinity from fresh to sea water, used in solution mining to dissolve salt.

3.1.80**weep hole**

A small opening or openings near the end of the brine string that helps to detect an imminent overflow by allowing product to enter the brine string and be detected prior to overflowing the cavern.

3.1.81**well**

A cased hole created to provide access to an underground cavern.

3.1.82**wellhead**

An assemblage of base plates, spools, crosses, valves, and other equipment placed on the surface (or intermediate or production) casing to control well flow.

3.1.83**working capacity**

The volume of liquid that can be injected or withdrawn from a cavern.

3.1.84**wireline**

An electrically conductive wire used to run logging tools into a well.

3.1.85**workover**

Major maintenance or remedial activity performed on an underground hydrocarbon storage well and cavern. A workover typically involves pulling some or all of the hanging string.

3.2 Acronyms and Abbreviations

For the purposes of this document, the following acronyms and abbreviations apply.

BHA bottom hole assembly

BHC borehole compensated [sonic]

BOP blowout preventer

CBL cement bond log

CCTV closed-circuit television

ESD emergency shutdown

GR gamma ray

H₂S hydrogen sulfide

ID inside diameter

K potassium

KCl potassium chloride

MAOP maximum allowable operating pressure

Mg magnesium

MgCl₂ magnesium chloride

MIT mechanical integrity test

NaCl sodium chloride

OCTG oil country tubular goods

OD outside diameter

OPP overpressure protection

ROP rate of penetration

SCADA supervisory control and data acquisition

SMRI Solution Mining Research Institute

SP spontaneous potential

TD total depth

Th thorium

Ur uranium

USDW underground source of drinking water

VSP vertical seismic profile

4 Overview of Underground Liquids Storage

4.1 General

Site selection for solution-mined underground storage is based on numerous considerations, including a study of the geologic formation to be utilized. Proper drilling and casing-cementing procedures are essential to ensure the integrity of the storage cavern. Cavern development is accomplished by injecting water to dissolve the salt mass and displace the resulting brine.

Before the product is injected initially, the storage cavern is full of brine. Injecting product displaces brine and maintains a liquid-filled cavern. The product is withdrawn from the cavern by displacing it with brine or water.

A simple diagram of a salt cavern used in liquid storage can be seen in Figure 1.

4.2 Functional Integrity

Functional integrity should be the goal of the design, construction, and operation phases of a cavern. Sound engineering practices such as those in this RP help guide operators, with the goal of ensuring a safe facility for all stakeholders and protection of the environment.

4.3 Overview of Major Steps in the Development of Liquid Storage Caverns

Major steps in developing salt caverns for liquid storage include:

- locating a salt structure suitable for cavern development;

- determining liquid storage capacities and flow rate capabilities;
- determining a project schedule, including in-service dates;
- designing, drilling, and equipping the cavern well;
- designing, drilling, and equipping water supply wells, circulating pumps, and brine disposal wells and facilities;
- designing, solution mining, testing, and placing the cavern into service;
- operating and maintaining the cavern well and cavern to ensure functional integrity.

Not all sedimentary basins contain salt deposits, limiting the areas available for cavern development. Selecting a site for solution-mined caverns involves many factors, including the suitability of a salt dome or salt formation's geological and geomechanical properties. These properties include the height and areal extent of salt, the percent of non-salt material within the salt formation, depth and geothermal temperature of the salt, the internal structure of the salt, and the strength of the salt when subjected to forces of compression and tension.

Drilling test boreholes and obtaining rock cores are among the ways these properties can be investigated. The geological characterization of the salt body can be accomplished through review of data from wells drilled in the area, as well as analysis of existing or newly acquired seismic data.

Once the desired storage capacity is determined, the size and shape of the cavern to store that volume can be designed. In general, combinations of overall cavern height, diameter, and depth are compared. Studies can be conducted on the mechanical strength of the salt to determine an effective, efficient, and stable cavern shape.

The required rate at which the liquid is to be injected or withdrawn from the cavern system determines the size of the cavern well and surface equipment. These rates are expressed in flow units, such as barrels per day, barrels per hour, gallons per minute, or pounds per hour.

With the flow rate requirements given, the size (or diameter) of the well into the cavern can be established. The required flow rate influences the diameter of the well due to factors such as acceptable frictional losses. Combinations of casing diameters, thicknesses, and strengths can be reviewed to find an effective design.

A project schedule including in-service dates is based on the time required to design, permit, and drill the cavern well; to solution mine; and to test the cavern. Once the facility design is completed, there can be significant lengths of time required to prepare and obtain the necessary regulatory permits and authorizations.

Drilling a cavern well to be used to develop and operate a cavern requires careful planning and execution. For cavern wells, the size of the holes bored in the earth are typically larger than required by other oilfield operations, such as exploration and production activities. The number and setting depths of well casings are also different than found in other oilfield operations due to the unique geologic settings and operating conditions of salt cavern wells.

Water supply and returned brine disposal facilities can be designed to supply the water and dispose of the brine during cavern development. Pumps, filters, meters, flow lines, and other surface equipment can be designed and installed to create a flow path from the water supply, down the cavern well, into the cavern, up the cavern well to the surface, and to the brine disposal facilities.

After drilling the cavern well, multiple concentric tubular steel casing strings are lowered into the well and suspended or hung from inside the wellhead and into the wellbore. The water supply pumping equipment can be hooked up to the wellhead to inject the water down through the tubular strings where it contacts the salt formation. The salt dissolves into the water, turning the water to brine. The pumps circulate the brine to the surface, where the brine exits the wellhead and flows to the disposal wells or a salt plant. During solution mining, it is critical that the roof of a cavern is prevented from dissolving by placing and floating a blanket material that does not dissolve salt (often gas, a liquid hydrocarbon, or mineral oil) on top of the water and brine in the cavern. Periodic monitoring of the size and shape of the cavern can be performed using sonar survey equipment. Once solution mining has been completed, the cavern and well are prepared for conversion to liquid service by installing a

wellhead specifically designed for liquid service and by performing a mechanical integrity test (MIT) of the cavern system, including the wellhead and wellbore tubulars. After a successful MIT, storage operations can commence.

The total cavern volume is determined by sonar survey. The total storage capacity of the cavern is the volume of liquid hydrocarbons that can be injected into the cavern interval without entering the brine string.

To ensure long-term, reliable service and safety of the public and to the environment, the integrity of the well and salt cavern system shall be maintained and monitored. Periodic integrity assessments should include the condition of the wellhead, the cemented production casing, the size and shape of the cavern, and the ability of the cavern system to contain the liquid stored within it.

These objectives are associated with corresponding design and construction requirements. The design process seeks to find the most effective combination of performance objectives and design, construction, and operational requirements.

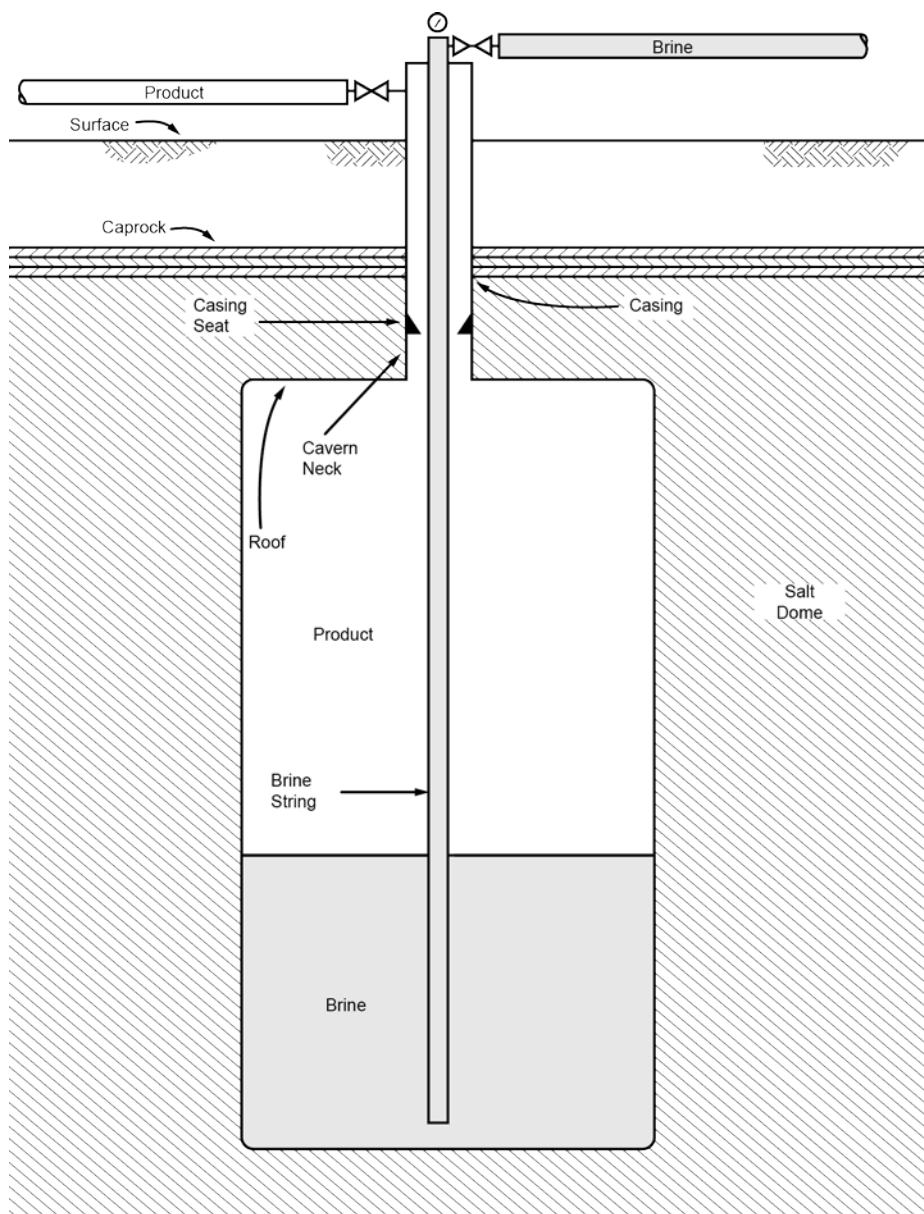


Figure 1—Simplified Salt Dome Storage Cavern Schematic

5 Geological and Geomechanical Evaluation

5.1 General Considerations

The first major step in developing salt caverns for liquid hydrocarbon storage is locating a salt deposit suitable for cavern development. Not all sedimentary basins contain salt deposits, resulting in limited areas of the U.S. that have suitable salt formations². When selecting a site for solution-mined caverns, an operator considers a number of factors, including locating a salt dome or salt formation with suitable geological and geomechanical properties. These properties include the thickness and lateral extent of salt, the percent of non-salt material within the salt formation, depth and geothermal temperature of the salt, the internal structure of the salt, and the strength of the salt when subjected to forces of compression and tension. Drilling test boreholes and obtaining rock cores are among the ways these properties can be investigated. The geological characterization of the salt body can be accomplished through review of data from existing wells drilled in the area, as well as analysis of existing or newly acquired seismic data.

5.2 Site Selection Criteria

5.2.1 General

Site selection for solution-mined liquid hydrocarbon storage caverns is based on numerous considerations, including at least the following items:

- a study of the geologic formation to be used;
- the availability of raw water for solution mining;
- opportunities for disposal of the produced brine;
- existing and planned use of the surface and subsurface.

If any of the key elements required for cavern construction and operation are not present at a particular site, cavern development at the site may not be practical or feasible.

5.2.2 Geologic Formation

The primary objective of the geological and geophysical site characterization is to determine the type (domal, bedded, or “tectonic”), geometry, and areal extent of the salt deposit and its ability to safely and economically contain liquid hydrocarbon storage caverns. Overlying and adjacent formations should be studied as part of the overall geological investigation. The deformation and strength properties, as well as the in-situ conditions (such as temperature and stress state), are important geomechanical considerations in the selection of an appropriate geologic formation for liquid storage caverns.

The salt deposit should have enough extent to ensure that:

- the liquid hydrocarbon storage caverns are sufficiently remote from the edge of the dome and, in the case of bedded salts, significant faulting, dissolution boundaries, and salt thinning.
- The liquid hydrocarbon storage caverns are sufficiently remote from the property boundary and adjacent caverns.
- The liquid hydrocarbon storage caverns are sufficiently remote from the top of salt and base of salt to ensure liquid hydrocarbon containment.

² Johnson, K. S. and S. Gonzales, 1978. *Salt Deposits in the United States and Regional Geologic Characteristics Important for Storage of Radioactive Waste*, Report Y/OWI/SUB-7414/1, Office of Waste Isolation, U.S. Department of Energy, Washington, DC

NOTE The determination as to whether the caverns are “sufficiently remote” depends on the expected operations in the caverns, the operations in existing or planned adjacent caverns, the geomechanical properties of the formations, and the in-situ conditions in the formations.

5.2.3 Availability of Raw Water for Solution Mining

A source of raw water with sufficient quantity, quality, and delivery rate should be available for solution mining of the liquid hydrocarbon storage caverns. Approximately seven to 10 barrels of fresh water are required to develop one barrel of cavern space. If saline or brackish water is used for solution mining, the water requirements can be greater. In addition to the water volume, the rate of delivery is also an important site selection consideration. For example, if cavern volume is to be developed rapidly, associated high water delivery rates are required. Supply rate requirements of 3000 gallons to 5000 gallons per minute for solution-mining are common.

5.2.4 Opportunities for Brine Disposal

Opportunities for brine disposal in volumes and at rates slightly greater than the water supply volumes and rates should be available at or near the site. Brine produced in the solution mining of liquid hydrocarbon storage caverns can be provided to a brine user or disposed in a subsurface formation or in bodies of saltwater, if located at a practical pipeline distance. The number of brine disposal wells required to dispose of the produced brine at the desired rate depends on the permeability and porosity of the formation, as well as other subsurface conditions, such as initial formation pressure, fracture gradient, proximity to faulting, and formation thickness.

NOTE In the U.S., federal and state programs and regulations may impact brine disposal options.

5.2.5 Existing and Planned Infrastructure

Existing and planned caverns and surface infrastructure should be included in the site selection process. Existing solution-mined caverns (for brine production, natural gas storage, or liquid hydrocarbon storage) can provide valuable information for site selection at a particular salt deposit. Internal faulting or shearing within the salt body and any potential irregularity in solution-mined cavern shapes can often be assessed by examining existing solution-mined caverns. Another key consideration in site selection is proximity to surface infrastructure (such as pipelines, three-phase electrical power, and roads and highways) that is required for the development and operation of liquid hydrocarbon storage caverns.

5.3 Geologic Site Characterization

A geological characterization of the site provides a framework to sufficiently understand the site geology, potential risk factors, and project feasibility. It also aids in the selection of well locations and provides input to the engineering design. Although this document pertains primarily to salt caverns, site characterizations for salt cavern projects also require characterization of brine disposal and water supply if they rely on geologic sources.

A geologic site characterization should delineate the geometry, thickness, and internal petrophysical character of the salt deposit and, if applicable, the brine disposal reservoir and water supply aquifer. Geologic site characterization requires an understanding of the depositional and structural framework of the geologic formations. The geologic framework established by a site characterization provides the basis for prediction of the geologic conditions in the subsurface that allows for locating cavern wells and identifying or managing geologic uncertainties. Limited resolution or uncertainty in the geologic model can equate to some level of increased risk that may need to be resolved with additional data or planning.

5.3.1 Subsurface Geologic Data

5.3.1.1 General

The data used in a geologic site characterization should incorporate subregional and site-specific data from all readily available sources. Initial feasibility studies rely upon existing available data, either proprietary or public domain. Geologic site characterizations are usually more detailed than feasibility studies, and acquisition of additional site-specific data can be required depending upon the quality and completeness of the existing data set. These additional data are most commonly obtained by drilling exploration wells and/or acquiring geophysical surveys.

Data can include, but are not limited to, the following:

- geologic literature and historic data (well records, geologic reports, scout tickets, driller's logs, daily drilling reports, older maps, etc.);
- open-hole well logs;
- core data;
- geophysical surveys.

5.3.1.2 Geologic Literature and Public Domain Data

Geologic site characterization should include a review of the available geologic literature, historical reports, and published maps to provide information regarding the local geology, historical information, and regional geologic context of the area. Additional data can be found in drilling reports, scout tickets, driller's logs, etc. Much of the historical information predates geophysical well logs and can provide information for older wells where the original data are no longer available.

5.3.1.3 Open-Hole Well Logs

5.3.1.3.1 General

A geologic site characterization should incorporate all available site-specific well logs that provide geologic data for the salt/reservoir/aquifers and overburden strata relevant to the project. Open-hole well logs acquired mainly during oil and gas exploration and exploitation activities form the basic data in most subsurface salt storage geologic investigations. Well log data can vary greatly in vintage, availability, type, quality, and density of coverage. Logs provide the basis for the correlation of formation tops used for mapping the subsurface geology and petrophysical data that are used to characterize the internal properties of the salt, caprock, and surrounding strata. Well logs can be obtained from company files, commercial sources, and some state agencies. See Annex A for additional information about open-hole well logs.

5.3.1.3.2 Well Logging Problems

An open-hole logging program to acquire useful and meaningful borehole data should be run in any new well drilled for the project. Log coverage should be continuous from the base of the surface casing to the total depth of the well unless logging an interval presents a risk to the well.

The specifics regarding log type and log intervals should be determined by the borehole geology, borehole conditions (borehole size and irregularity, drilling fluid, etc.), drilling program, and the data requirements of the project. A qualified professional should design the logging program and review the log data as it is being acquired to make sure the header information is correct and the log data are of good quality.

NOTE The type of drilling fluid, large borehole size, and borehole irregularity impact the quality of many open-hole well logs.

The log suite for geologic characterization of a salt deposit and the overlying strata should include gamma ray (GR), litho-density, neutron, dipole, or full-wave sonic, and caliper logs. This well log suite should provide information on salt purity, non-salt stringers or interbeds, and the presence of potassium-magnesium (K-Mg) salts that are highly soluble and creep prone. These logs are also useful to characterize any caprock and the strata overlying and surrounding the salt. Other types of wireline logs may be required as dictated by the local geology and the type of data required.

NOTE Spectral gamma ray logs break down the gamma ray signature into components of potassium, thorium, and uranium (K, Th, and Ur) that can help distinguish K-Mg salts from other impurities, such as clay.

Spontaneous potential (SP) and some type of resistivity log should be run in strata overlying the salt to help identify the base of fresh water and any hydrocarbon zones. Surrounding hydrocarbon or ground water wells

specific area often have a preferred log type, such as resistivity, sonic, or density. The preferred log type should also be run to provide the basis for correlation with surrounding well control.

NOTE 1 While resistivity logs are useful for characterizing strata outside the salt (especially for identifying fresh water zones, permeable zones, and hydrocarbon zones), they either do not work or are not particularly useful in salt. SP tools do not work in salt but can be used to indicate the presence of salt in historic well logs.

NOTE 2 Halite, anhydrite, gypsum, and clean sandstones are indistinguishable on gamma ray logs and require other data such as density or sonic logs to distinguish between them.

Check shot surveys and sonic logs can be useful to interpret or depth-convert seismic data.

While not an open-hole geophysical log, a mud or cuttings log can be useful for lithologic identification, for helping determine core or casing points prior to wireline logging, and for detecting the presence of gas while drilling. They are also useful for recording penetration rate, core intervals, and lost circulation zones.

5.3.1.3.3 Modeled Mineralogy Logs

Modeled mineralogy logs are derived from wireline log data and may be used in salt to assist with solution-mining simulations. The mineral components to be included in the model are determined by the geology of the interval being modeled and the available log data. A modeled mineralogy log is generated from well log data to identify the type and gross distribution of insoluble and impurity material within the salt. The more log types available, the more components that can be accommodated by the model.

Modeled mineralogy logs should be calibrated with core data, such as weight percent insoluble material, X-ray diffraction, petrographic, and wet chemistry data. These logs are non-unique solutions and proper calibration requires good core log integration.

5.3.1.4 Core

5.3.1.4.1 General

Salt cavern fields should have core data for the salt and any brine disposal zones. Core data from key units, such as confining formations, caprock, and disposal zones, can also be of value depending upon the site geology and data requirements. Core is the geologic equivalent of “ground truth” for subsurface geology. Much geologic information, such as geomechanical properties, salt fabric, structural features, anomalous salt, and the actual distribution of insoluble material within the salt can only be determined from core. Most importantly, core test data provides the geomechanical properties of salt and other key rock units that are input into geomechanical models used to evaluate cavern stability, subsidence, and the operating pressures in a storage cavern. While some petrophysical data can be acquired from logs, petrologic and mineralogic analysis of both salt and non-salt core can be used in the calibration of open-hole well logs and other geophysical data.

For brine disposal reservoir assessment, core data may also provide direct permeability information that cannot be obtained from well logs.

5.3.1.4.2 Geologic Considerations for Core Acquisition

If not already available, core can only be acquired with the drilling of new wells. The depth interval and amount of core to be cut should be determined on a well-to-well basis depending upon the needs of the project and the site geology. If data are not available from nearby wells, the core may be cut solely based on the expected depth of the cavern interval and geology in the immediate area. The amount cored should be sufficient to anticipate the amount of material required for core testing and account for damaged core, rubble, lost core, anomalous salt, non-salt interbeds and stringers, and other factors that may limit its usefulness for testing. As the core is only obtainable by drilling a well, it is better to cut more instead of too little. Poor sampling or insufficient core can result in skewed test results that could detrimentally impact the cavern operating conditions.

Salt core should be 4 in. diameter conventional core to be suitable for geomechanical testing. Sidewall cores (either percussion or rotary) are of little value in salt because percussion samples are highly damaged and rotary

cores are too small to test for salt mechanical properties (see 5.4). Sidewall cores can be useful to obtain petrologic data for non-salt interbeds and brine disposal reservoirs.

If the geologist anticipates variable lithology or significant interbeds, sufficient core should be cut to sample the various major zones, especially weak points such as bed contacts. In domal salt where the internal banding is near vertical, different wells in a cavern field can exhibit significantly different properties, and some core should be recovered in each cavern well. In bedded salt, if the salt is stratigraphically similar across the storage field, the entire cavern interval should be cored in the first well, with spot coring in subsequent wells.

Liners or aluminum sleeves should be used to help maximize core recovery, properly locate rubble zones, and minimize or expedite core handling in the field. Reduced core handling in the field helps minimize core damage and exposure of salt to the elements while aiding in core transport, inventory, and reconstruction. Liners help with the recovery of rubble and maintain the rubble in its position relative to the rest of the core. In the field, the liners can be cut into segments, end capped, and depth marked, minimizing exposure to the elements.

NOTE The location and amount of rubble can be the result of coring issues or can be an indicator of geologically problematic or anomalous salt. Having the rubble preserved in proper context can help identify geologically problematic zones within the salt.

5.3.1.4.3 Initial Core Review

The core should be documented by a detailed core description and photography prior to any sampling or destructive testing. This provides a permanent record of the core intervals that were later removed for testing. Photographs and core descriptions allow assessment without pulling core out of storage.

The core should be reconstructed, cleaned, depth marked, and described in detail out of the weather under constant conditions of lighting. The fit or lack of fit between adjacent core pieces should be noted. A double red/black vertical line down the core axis may aid in determining the up direction, especially if core samples are removed.

A core gamma log may be run in the lab while the core is still in the liner or after it has been extruded and reconstructed. Core gamma logs are not useful for Gulf Coast domal salt where the primary non-halite impurity is anhydrite because anhydrite and halite have similar gamma ray signatures. However, in bedded salts or domal salt with impurities other than anhydrite/gypsum (for example, shale or potash), core gamma logs are useful for core-log correlation.

The core should be photographed in its entirety prior to any sampling. The photographs should be in constant lighting, out of the weather, and taken with a high-quality camera. Photographs should be high resolution with readily legible labels for the well name, API or serial number, date, core number, and depth interval of the core in the photo. The core photographs should also have depth scales and a color calibration bar. The photographs should be archived in the permanent project files so that they are available for review later.

The core should be described in detail prior to any destructive testing or sampling. The core description should provide a record of the visual examination of the entire core, including but not limited to core condition, lithology, color, fabric, grain size, grain orientation, impurity content, and other notable geologic features observed in the core, such as faulting, fractures, rubble, dilated salt, zones of highly strained or sheared salt, and other anomalous features.

Describing whole cores is more difficult and provides less detail than describing slabbed core. Many core tests, especially on salt cores, can only be performed on whole cores, so caution should be used when deciding which intervals to slab. Slabbing often damages salt cores. Slabbing is not as detrimental to non-salt cores and can aid with observing the details of the rock. Non-salt core testing can often be done on plug samples or subcores if they are at least 1 7/8 inches in diameter (see Section 5.4.2.3).

5.3.1.4.4 Core Sampling

Sampling of core for testing from each type of salt should be done on visually similar salt core with regard to grain fabric and impurity content. After review of the core, different salt types can be identified based on visual examination. Key discriminators in salt include grain fabric, grain size, and the type and distribution of impurity

content. Salt core of each major type of geologically representative core should be selected for testing as determined by the geologist. The distribution and composition of impurity material can impact the geomechanical properties of rock salt. Grain fabric can be an indicator of deformational history or anomalous salt, both of which may be reflected in the geomechanical test results. Non-salt core testing is determined based upon geologic and engineering considerations depending upon the type of information required.

Sufficient material for each salt type should be selected for geomechanical testing to allow one or more complete test suites as outlined in Section 5.4. Individual core pieces selected for testing should be at least 1 ft in length, except for those selected for Brazilian indirect tension testing (see Section 5.4.2.4), which can be as short as 4 inches. Sampling should avoid features such as impurity stringers, large intraclasts, and structural anomalies that might localize deformation or potentially skew the creep and strength test results. Under-gauge core due to exposure to undersaturated brine and core damaged during drilling should not be used as test samples.

5.3.1.4.5 Core Testing

The goal of the core testing program is to characterize the geomechanical and geologic properties of each of the identified salt types (i.e. facies) and non-salt units within the radius of influence of the cavern. See Section 5.4 with regard to geomechanical core testing and protocols.

Before testing, the prepared geomechanical test samples should be photographed to provide a record of the pre-test sample, and sonic/density measurements may be made. Post-test photographs should also be taken to facilitate the review of sample failure/deformation to determine if the test results could have been influenced by non-salt impurities or localized strain/failure.

Core testing should be done to help characterize the insoluble content. This information can assist with the preparation of a solution-mining plan, log calibration for modeled mineralogy logs, solids control of the brine stream, and evaluating potential for formation damage in brine disposal reservoirs.

Additional testing to characterize the insoluble content within the salt should include a determination of the weight percent of insolubles, X-ray diffraction to determine the mineralogy of the insoluble fraction within the salt, and particle grain-size analysis to determine the grain size of insoluble components. With regards to coordinating this testing with the geomechanical sampling, end cuts from the geomechanical test samples may be used for the above-mentioned tests.

In complex salts with high impurity content, dissolution testing may also be performed to obtain a dissolution rate relative to clean halite for input into the solution-mining model.

5.3.1.4.6 Core Log Integration

The first task of core log integration should be to reconcile the core depth (driller's depth) with the open-hole well log depth, which can differ by several feet or tens of feet. The typical method is to run a core gamma log in the lab. Core log integration often results in a bulk shift of the core depth to coincide with log depth. If individual core pieces exhibit lack of fit with the adjacent pieces (i.e. lost or missing core), this bulk shift can vary within the cored interval.

In clean domal salt, it is often impossible to reconcile core depth and log depth using a gamma ray (GR) log because anhydrite/gypsum have similar GR signatures to halite. If impurity stringers or banding exist, they can be correlated with GR, density, or sonic log data depending upon the type and amount of the impurities. In the case of some bedded salt with discrete, well-defined layers, the core log integration can be based strictly upon lithology without using a core gamma log.

The core should be used in conjunction with the full suite of available open-hole well logs. Once the core depth and log depth have been reconciled, individual core test data, core intervals, rubble zones, and other significant features within the core can be directly located on the well logs for analysis. Good core log integration assists with the characterization of non-cored intervals based solely upon well log information.

5.3.1.5 Geophysical Surveys

5.3.1.5.1 General

Geophysical surveys are remote sensing methodologies that can help resolve the subsurface geology where well data are sparse or insufficient. Geophysical surveys can be either specifically performed for a project or purchased or leased if nonproprietary, commercial data for the locale are available.

5.3.1.5.2 Purchase or Lease of Commercial Data

Commercial geophysical data may be available for purchase or lease. The quality of the data should be assessed by a knowledgeable geophysicist or geologist. The acquisition and processing parameters that were originally used may not address the concerns or depth interval of interest for salt cavern storage, and may be unsuitable or require reprocessing.

5.3.1.5.3 Data Acquisition and Processing

Acquiring new geophysical survey data may be necessary. This may occur in a later phase of the geologic investigation after sufficient work has been done to determine the existing data gaps and the nature of the data that need to be acquired.

The site geology, existing data coverage, depth of investigation, contrast of the geologic units of interest, geometry of the structure to be imaged, and surface access should be evaluated prior to selecting a particular geophysical survey method. A qualified geophysicist or geologist should determine the appropriate methodology, survey design, and processing of the data. It is important to consider the nature of the investigation and the local geology to determine if the selected methodology can adequately provide the resolution needed to image the interval of interest in the subsurface.

NOTE The geophysical resolution of a bed or structure in the subsurface usually depends upon the geometry (thickness, depth, and orientation) of the object being imaged, its contrast (sonic velocity, density, etc.) with other strata or rock types, and the acquisition parameters of the chosen methodology. When considering performing a geophysical survey, existing culture and terrain are important considerations.

Typical geophysical methods useful for underground storage in salt caverns are:

- 2-D and 3-D seismic surveys,
- borehole seismic surveys,
- gravity surveys, and
- borehole acoustic/radar surveys.

Regardless of the methodology, geophysical surveys should be calibrated and validated with well control and other “ground truth” data because the data are highly model- and processing-dependent.

5.3.1.5.4 2-D and 3-D Seismic Surveys

Seismic reflection surveys measure the travel time of elastic waves through rock strata and currently are the most commonly used geophysical method for the subsurface mapping of salt structures in the U.S. Because of the limitations of data coverage in two dimensions, 2-D seismic is considered less useful than 3-D seismic in geologically complex areas because 3-D seismic provides complete coverage of the survey area. 3-D surveys are also considered better for salt domes because they provide a larger data volume, do not require extrapolation between individual lines, and typically do a better job locating steeply dipping events into their proper locations.

Salt domes present several challenges with regard to seismic surveys because of the near-vertical sides of the salt stock, the potential for salt overhangs, and the associated structural complexity. Both 2-D and 3-D seismic surveys usually need long offsets to image near vertical edges and steeply dipping strata.

lines are often acquired in radial patterns to image the edge of salt. For steeply dipping and structurally complex structures, 2-D seismic surveys often suffer from out-of-plane events.

Seismic data are acquired as time and velocity data or a velocity model is required to convert the data to depth. The depth conversion is dependent upon the quality of the existing velocity model. Seismic interpretations should be tied to existing well data.

5.3.1.5.5 Borehole Seismic Surveys

Borehole seismic can be a useful exploration tool for salt cavern projects. Borehole seismic surveys most commonly used for salt include check shot surveys, vertical seismic profiles (VSPs), salt proximity surveys, and cross-well tomography. These methods require access to one or more boreholes. Choice of methodology depends upon the objectives of the study, tool availability, well availability, borehole conditions, and local geology.

Check shot surveys are most useful to acquire velocity data in the borehole for velocity models and time-depth conversions of 2-D and 3-D seismic surveys.

VSPs can be used to help locate the edge of the dome or salt deposit. They are sensitive to source/receiver placement and the geometry of the interface to be imaged. VSPs often suffer from the inability to image the salt flank at the cavern level due to geometric constraints unless the well in which the VSP is being acquired is much deeper than the depth being imaged. They may be able to image features within the salt deposit depending upon thickness, acoustic contrast, and geometry; other borehole data, such as open-hole well logs and core, may be needed to characterize the geologic feature that created the VSP response. For cross-well tomography, the source and receivers are each placed in adjacent wells.

5.3.1.5.6 Gravity Surveys

Because of salt's low density, gravity surveys can be useful for delineating salt deposits if there is sufficient density contrast between the salt and surrounding rock mass. The ability of gravity to resolve a salt body also depends upon the size and depth of the salt mass. While often useful to identify areas of more salt, potentially cleaner salt, or the general boundaries of a salt deposit, the resolution capabilities of gravity surveys are limited in terms of detail.

5.3.1.5.7 Borehole Acoustic and Radar Surveys

Geologic structure within salt hundreds of feet from a borehole can be interpreted using borehole acoustic and radar surveys. Both methods use the reflection of waves transmitted from a single borehole to image internal structure if there are layers or bands within the salt that have suitable geometry, thickness, and contrast to be adequately imaged and resolved. The primary difference between the two methods is the frequency of the waves used in the surveys. Acoustic surveys use waves in the kilohertz range, whereas radar surveys use ultra-high-frequency radio waves. Borehole radar has been used in Europe in a similar fashion to VSPs, but tool availability may be limited in the U.S.

5.3.2 Exploration Programs

After review of the initial assessment based upon the available data, it may be determined that additional subsurface data are needed for the feasibility study or site characterization.

Exploration programs should be designed based upon an assessment of the existing data and aim to acquire pertinent useful data in a cost-effective fashion requiring consideration of the site-specific geologic setting, available geologic data (quality, distribution, and density), and the usefulness and limitations of the various methodologies considered. Typical exploration programs can include the drilling of test wells to acquire open-hole well log data, borehole geophysical surveys, core, and well test data for a specific location. Geophysical surveys, such as 2-D and 3-D seismic, can be used to cover larger areas away from known well control or where gaps exist in the well data.

5.3.3 Geologic Assessment and Integration

5.3.3.1 General

A set of subsurface geologic maps is not the end product in itself, but a means to formulate and communicate geologic interpretations. They are used to establish project feasibility, design criteria, select well locations, and identify and manage potential geologic risk.

There are always interpretational options when constructing subsurface geologic maps, so mapping to concepts and using multiple lines of supporting data (drilling records, cavern sonar surveys, lost circulation, etc.) should be incorporated into mapping to constrain interpretational options.

Maps and other geologic displays should be adjusted with each other and be internally consistent. A stronger interpretation is often obtained by using a coordinated suite of maps and displays incorporating multiple horizons, as opposed to a few stand-alone displays.

While the general approach is similar for all salt deposits, the exact methodology should be determined on a site-by-site basis depending upon the geologic setting and project requirements, as well as the quality, type, and distribution of the available data. Salt dome characterizations generally emphasize edge (flank) definition, salt quality (mechanical and compositional), lateral salt variation, internal banding, shear zones, and differential salt movement. There is no stratigraphic component associated with salt domes as the original bedding has been destroyed and is replaced by internal shear banding. Bedded salt characterizations, while also concerned with salt quality, generally emphasize stratigraphy, dissolution fronts, bed thickness, strength and competence of interbeds, and lithologic controls on solubility and cavern stability. Characterization of highly deformed, tectonic salt deposits may include a strong structural component, as well as varying degrees of stratigraphic assessment.

5.3.3.2 Geologic Uncertainty

A geologic site characterization should assess the uncertainty in the characterization based upon the existing data and current geologic model. Elements of uncertainty that pose risks in salt include but are not limited to the edge of salt, shear zones, faults, high-impurity zones, K-Mg salts, weak zones, zones with high creep potential, dissolution or collapse zones, nearby wells, or other subsurface activities. The edge of salt is one of the primary elements of geologic risk for salt domes. Additional buffer should be assessed on a site-by-site basis by a qualified geologist to account for uncertainty in locating the exact edge of salt and to allow for the possibility that salt quality with regard to geomechanical strength properties and impurity content tends to degrade toward the edge of salt. Caprock on salt domes can contain lost circulation zones, faulting, and H₂S that can pose risks to hole stability and safety during drilling and to long-term stability of well casing.

In the case of brine disposal, potential risk factors include but are not limited to nearby wells and subsurface activities, the presence of hydrocarbons, faulting, limited reservoir volume, permeability pathways and barriers, potential leak paths, and proximity to underground sources of drinking water.

Characterization of water supply includes not only understanding the hydrogeologic capabilities/limitations of the aquifer and local water use, but also the potential for contamination if the aquifer is not adequately isolated from the brine disposal reservoir and storage caverns.

5.3.3.3 Geologic Maps and Displays

Correlating formations or marker horizons between wells using open-hole well logs and geophysical survey data allows creation of subsurface geologic maps, cross-sections, and other displays that are used to assess and characterize the site geology. Correlation markers may be presented on a type log or cross-section. The type and number of geologic displays utilized depends upon the site geology, the data available, the scope of the assessment, the requirements of the project, and the type of information that needs to be communicated.

A geologic site characterization should utilize accurate well coordinates and a good quality base map showing well locations, property boundaries, and land grid. All mapping and displays should conform to accepted standards and methodologies for subsurface geologic mapping. Maps and cross-sections should be referenced to a suitable datum (usually mean sea level), properly annotated, and scaled appropriately. Datums, scales, orientation (usually North direction), contour intervals, map type, date of origin, and author should be clearly

defined and legible. Key data (e.g. formation tops, contour labels, well identifiers) should be annotated and readily legible.

The most common map type for salt dome storage projects is the salt structure or top of salt map. Top of caprock and caprock isopach maps are also recommended if sufficient data are available; useful information on the geologically recent behavior of the salt dome can be derived from caprock maps. Profiles derived from the maps showing the cavern relative to both the caprock and salt can also be of use to refine the interpretation and convey geologic information.

In the case of bedded salt, structure maps for both the top and base of the salt, plus a salt isopach map, should be developed if the data permit. If multiple salt layers and significant interbeds are present, structure and isopach maps for each of the major units may be warranted. A series of cross-sections showing the continuity and variation of the salt and interbeds can also be useful.

NOTE When mapping a salt dome or salt deposit, it is just as important to map where the salt is not encountered (negative well control) as it is to map the actual salt tops.

Brine disposal and raw water sources are also key components of a salt storage project. In addition to structure and isopach maps of key overburden or flank strata, additional maps may be warranted, such as base of groundwater, porosity maps, net sand, lithofacies, and fault plane maps.

5.3.3.4 Geologic Report

A geologic report should be prepared that includes all pertinent supporting data to document the basis for the geologic interpretation. The report should include a discussion of scope, data reviewed, methodology, analysis, conclusions, and recommendations, with all supporting data and subsidiary reports supplied as appendices. All displays should be legible and annotated with the relevant data.

All supporting data should be referenced, and care should be taken when handling proprietary data. Many subsurface data are subject to confidentiality, copyright, and licensing agreements. This is especially true when utilizing and presenting seismic survey data, the use of which is usually subject to licensing agreements and may require permission and/or redaction.

5.4 Geomechanical Site Evaluation

5.4.1 General

All storage caverns in salt progressively decrease in volume because salt continuously deforms or creeps when subjected to the shear stresses induced by cavern development and operations³. The stresses in salt redistribute as it creeps; if there are non-salt units near the creeping salt, loads transferred from the salt typically accumulate in those units. Loads transferred to non-salt units can cause them to fail if the loads exceed the strength of the non-salt rock. Salt can also progressively microfracture and dilate if the shear stress exceeds its dilation strength. Microfracturing, which is also called damage, weakens the salt and increases its permeability. The initial, in situ conditions in the salt and non-salt rock surrounding a storage cavern strongly affect the rate of salt creep and the potential for salt damage and non-salt failure. Salt dilation is of much less concern for a liquid storage cavern than for a natural gas storage cavern.

To assess the structural stability and closure rate of a liquid hydrocarbon storage cavern, the mechanical properties of the various rock types and the in-situ conditions should be determined in a geomechanical review and characterization of the site. These properties and conditions are key elements in developing a representative and accurate numerical model of a storage cavern.

The following site-specific geomechanical properties should be determined by laboratory testing of representative core samples:

³ Liquid hydrocarbon storage caverns typically exhibit an apparent increase in cavern volume owing to the incremental leaching associated with slightly undersaturated product displacement brine.

- elastic and strength properties of both salt and non-salt samples; and
- creep characteristics of salt samples.

In situ states of stress and temperature should be determined because accurate prediction of the creep deformation and potential for salt damage depends on these in situ conditions, especially in the depth interval of the storage cavern. If there are non-salt units within the radius of influence of the cavern, the potential for their failure also depends on the in-situ states of stress in them. In situ temperature has a minimal effect on the mechanical response of non-salt rock types.

5.4.2 Laboratory Testing of Geomechanical Properties

5.4.2.1 Testing Practices

The precision of laboratory tests is dependent on the competence of the personnel performing them and on the suitability of the equipment and facilities used. Agencies that meet the criteria of ASTM D3740⁴ are considered capable of competent and objective testing, although compliance with D3740 does not in itself assure reliable testing. Reliable testing depends on many factors, and ASTM D3740 provides a means for evaluating some of those factors.

5.4.2.2 Representative Samples

Both salt and non-salt rock are inherently heterogeneous, and their mechanical properties can vary appreciably, even within the same geological formation or member. Consequently, test specimens representative of each rock type under consideration should be selected from the available core based on visual observations of mineral constituents, grain size and shape, bedding, and pore structure; measurements of bulk density and ultrasonic velocity; and correlation of specimen location to open-hole well logs.

Salt specimens from the cavern interval at the storage site should be used for testing of salt properties. Non-salt specimens should be selected from within the cavern interval and from a distance of at least two cavern diameters.

A sufficient number of specimens of each rock type should be tested to estimate average mechanical properties and to assess the variability in the properties. Although standard statistical methods are available to determine the number of tests required to obtain a specific confidence level, it may not be economically feasible to achieve statistically valid results for each property. The judgment of experienced professionals in rock mechanics may be required to supplement and interpret the laboratory test results.

5.4.2.3 Testing Samples

Cylindrical specimens shall be prepared for testing with procedures that meet or exceed ASTM D4543. For triaxial test specimens, this standard specifies that if this test is used, a specimen shall have a length-to-diameter ratio of 2.0 to 2.5 and a diameter of not less than 1½ inches. In addition, it is desirable that the diameter be at least 10 times the size of the largest mineral grain. The grain size of non-salt rock generally is small enough that 2-in. diameter specimens typically satisfy this recommendation. For salt, a specimen diameter of nominally 4 in. should be considered the minimum necessary to satisfy the diameter recommendation of ASTM D4543 because large grain sizes are often encountered in rock salt.

Core retrieval, packing, shipping, unpacking, and specimen preparation can cause loosening of salt grains and/or formation of microfractures that can reduce the inherent dilation strength of salt specimens. Preconditioning test specimens for several days under hydrostatic conditions with axial and confining pressures of 3000 psi has been

⁴ ASTM D3740, *Standard Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction*

demonstrated to mitigate or heal preexisting specimen damage, yielding more repeatable and somewhat higher dilation strengths in triaxial compression tests⁵.

5.4.2.4 Brazilian Indirect Tension Tests

Tensile strength is obtained by the application of a uniaxial tensile load to a specimen with a cylindrical cross-section. The application of a direct tensile load to a rock specimen is difficult and expensive for routine testing. Consequently, the Brazilian indirect tension test should be used to determine the apparent tensile strength of both salt and non-salt samples because this test is simple, reliable, and fairly inexpensive.

If a Brazilian indirect tension test is performed, it shall be performed and interpreted with a procedure that meets or exceeds the method specified by ASTM D3967. Although tensile strength is not typically used in geomechanical analyses because the loads around a liquid hydrocarbon storage cavern are, in general, compressive, the apparent tensile strength is a useful measure for comparisons between rock types and for comparing variations in rock strength from one location to another. If tensile stresses are predicted around a cavern, the apparent tensile strength may be used to estimate the rock's propensity for tensile failure.

5.4.2.5 Triaxial Compression Tests

5.4.2.5.1 General

In a triaxial compression test, a cylindrical specimen jacketed with a flexible, impermeable membrane is placed in a fluid-filled chamber that applies a confining pressure to the specimen's lateral surfaces and in a loading frame that applies a compressive axial stress. Triaxial compression tests are used to determine:

- static elastic moduli (e.g. Young's modulus and Poisson's ratio) of salt and non-salt specimens;
- dilation strength of salt specimens; and
- compressive strength of non-salt rock specimens.

These properties are used in numerical simulations, as well as for comparisons between different sites, rock types, and variations in properties from one horizon to another.

If a triaxial compression test is performed, it shall be performed and interpreted with a procedure that meets or exceeds the method specified by ASTM D7012. This recommended practice covers both uniaxial (unconfined) compression and confined compression tests. Although ASTM D7012 provides for testing at elevated temperatures, testing at room temperature should be adequate for determining the properties required in simulations of liquid hydrocarbon storage caverns.

ASTM D7012 covers the determination of the ultimate compressive strength of intact rock specimens. To determine the dilation strength of salt, the axial stress should be increased until inelastic, dilatant volumetric strain is measured. The onset of dilation (microfracturing) occurs at axial stresses substantially less than the ultimate strength of the salt. The axial stress at which inelastic dilation is observed is defined as the dilation strength at the confining pressure applied in the test.

ASTM D7012 specifies that at least three confined compression tests, each at a different confining pressure, should be conducted on essentially identical specimens of each rock type. Replicate tests at the same conditions may be required to establish reliable trends in the compressive strength as a function of confining pressure because of the heterogeneity that is inherent in rock and the scatter in the results that is often encountered. The unconfined and confined compressive strengths determined for each rock type should be reduced to a Mohr envelope that describes the variation of the rock type's compressive strength as a function of confining pressure.

⁵ DeVries, K. L., 2010. "Testing for the Dilation Strength of Salt—Final Report, 1 July 2008, RSI-2109," prepared by RESPEC, Rapid City, South Dakota, for Gas Storage Technology Consortium, University Park, Pennsylvania

5.4.2.5.2 Elastic Moduli and Dilation Strength of Salt

Salt specimens should be tested in a confined state because salt has the propensity to microfracture at relatively small axial stresses in unconfined tests. In confined compression tests, the difference between the axial stress and confining pressure should be increased rapidly to minimize creep deformation during the tests (e.g. using a constant axial strain rate of 10^{-4} per second). If unconfined compression tests are performed, they should only be used to determine index values for simple comparisons of salt properties from different locations and depths.

The static elastic moduli should be determined from the axial and radial strains measured during unload-reload cycles inserted into the loading path, as recommended in ASTM D7012 for rocks (such as potash and salt) that undergo significant inelastic strains during triaxial compression tests. The elastic moduli are determined from the linear portions of the stress-strain responses measured during reloading.

NOTE For triaxial compression tests on salt, Mellegard and Pfeifle⁶ recommend an alternate load path in which the mean stress in the specimen is maintained at a constant value by decreasing the confining pressure at twice the rate that the axial stress is increased. During conventional tests performed according to ASTM D7012, the confining pressure is maintained at a constant value while the axial stress is increased. By maintaining a constant mean stress during the course of the test, the elastic volumetric strain is suppressed, and the onset of inelastic dilatant strain is observed more definitively.

At least three confined compression tests should be conducted on similar salt specimens, each at a different confining pressure (or mean stress for constant mean stress testing), to define the variation of dilation strength of the salt as a function of mean stress. Replicate tests at the same conditions may be required to establish reliable trends in the dilation strength as a function of mean stress because of the heterogeneity typical in salt deposits and the scatter in the results that is often encountered.

The static elastic moduli and the unconfined and confined compressive strengths of non-salt rock types within the radius of influence of liquid hydrocarbon storage caverns should be determined. The unconfined strength is particularly useful for comparisons between rock types and for evaluating variability within a non-salt unit. In numerical simulations, deformation and strength properties determined from laboratory tests on non-salt cores should be employed with proper judgment; laboratory values may not accurately represent rock mass properties that are influenced by joints, faults, inhomogeneities, and other factors not present in laboratory specimens.

The difference between the axial stress and confining pressure should be increased rapidly and at a steady rate during triaxial compression tests on non-salt specimens. If the stress-strain response measured during initial loading exhibits significant nonlinearity, unload-reload cycles should be inserted into the load path to determine the elastic moduli in a manner similar to the methodology described for salt testing. ASTM D7012 specifies that the stress rate or strain rate should be selected to produce failure of a typical test specimen in unconfined compression in a test time between 2 and 15 minutes. The selected stress rate or strain rate for a given rock type should be used for all tests of the rock type in the investigation.

5.4.2.6 Triaxial Creep Tests of Salt

The predominant mechanism of deformation in salt surrounding liquid hydrocarbon storage caverns is time-dependent, viscoplastic deformation referred to as "creep." The creep rate of salt is strongly dependent upon the Von Mises effective stress, which is a three-dimensional measure of shear stress, and upon the temperature of the salt. In a triaxial creep test, a constant temperature and effective stress (difference between axial stress and confining pressure) is applied to a cylindrical salt specimen, and the time-dependent creep deformations are measured. Triaxial creep tests are used primarily for deriving a creep model that describes the creep rate of a salt deposit as a function of effective (shear) stress, temperature, and time. The creep model is used in numerical simulations of caverns in the salt, as well as to compare different salts and variations in salt response from one location to another.

⁶ Mellegard, K. D. and T. W. Pfeifle, 1999. "Laboratory Evaluation of Mechanical Properties of Rock Using an Automated Triaxial Compression Test with a Constant Mean Stress Criterion," *Nondestructive and Automated Testing for Soil and Rock Properties*, ASTM STP 1350, W. A. Marr and C. E. Fairhurst, Eds., American Society of Testing and Materials, West Conshohocken, Pennsylvania, pp. 247–258

If a triaxial creep test is performed, it shall be performed with a procedure that meets or exceeds the triaxial compression method specified by ASTM D7070. Because of salt's propensity to microfracture (dilate), salt should be tested in a confined state with a confining pressure greater than the difference between the axial stress and the confining pressure (equivalently, a confining pressure greater than one-half of the axial stress). Constant true-stress testing, in which the applied loads are adjusted to compensate for specimen deformation, should be used for triaxial creep tests on salt specimens because the creep strains often exceed 1 %.

The duration of a creep test at a constant effective stress and temperature should be sufficient for the axial strain rate to approach steady state. Typically, a creep test on a salt specimen requires 30 days or more to approach the steady-state creep rate.

At least three triaxial creep tests should be conducted on similar salt specimens, each at the same temperature but at different effective stresses, to define the variation in creep response as a function of effective stress. Replicate tests at the same conditions may be required to establish reliable trends in the creep response as a function of effective stress because of the heterogeneity typical in salt deposits and the scatter in the results that is often encountered.

The suite of triaxial creep tests should be performed at a temperature representative of the in-situ temperature around the liquid hydrocarbon storage cavern. Alternatively, additional triaxial creep tests may be performed over a range of temperatures to determine the variation in creep response as a function of temperature.

5.4.3 In Situ Temperature

If available, a temperature log performed in a borehole through the cavern interval should be used to establish the in-situ distribution of temperature. Temperature logging performed soon after completion of a borehole consistently underestimates the in-situ temperatures because the fluids circulated during drilling cool the borehole surface and the surrounding formations. Reliable measurements of the in-situ temperature distribution require waiting days or even weeks for the fluid in the borehole to heat up to static conditions representative of the initial geothermal temperatures in the formations. Ratigan and Blair ⁷ recommend delaying temperature logging as long as practical, but for at least 3 days to 5 days after drilling is complete. Various techniques have also been used to correct a series of temperature logs in a borehole to static conditions by treating temperature as a transient function and extrapolating to steady-state conditions⁸.

If reliable temperature logs are not available, regional databases of geothermal temperature and flux should be reviewed and used to develop preliminary estimates of in situ temperature. Regional geothermal data may not be representative of the conditions in salt domes because salt's thermal conductivity typically is two to three times greater than the thermal conductivities of the sedimentary deposits surrounding the dome. Many salt domes have also been investigated as hosts for heat generating, high-level radioactive waste repositories. Literature from these scientific investigations often includes measurements of the geothermal conditions in the salt domes.

5.4.4 In Situ Stress

The in-situ distribution of vertical stress should be evaluated by integrating a formation density log from the ground surface through the depth interval of the liquid hydrocarbon storage cavern. In salt deposits, it is generally accepted that the in-situ stress state is isotropic with the horizontal stress components essentially equal to the vertical stress because salt creep over geological time frames effectively removes any differences in the horizontal and vertical stress components.

In non-salt units, significant differences between the vertical and horizontal stress components can be sustained over geological time frames because non-salt rock types do not creep appreciably. Because the processes controlling the horizontal components of in situ stress (e.g., erosion, sedimentation, and tectonism) tend to be

⁷ Ratigan, J. L. and R. Blair, 1994. "Temperature Logging in Drillholes in Domal Salt," Solution Mining Research Institute Fall Meeting, Hannover, Germany

⁸ Prenskey, S., 1992. "Temperature Measurements in Boreholes: An Overview of Engineering and Scientific Applications," *The Log Analyst*, Vol. 33, No. 3, pp. 313-333

regional, reliable estimates of their principal values and directions may be available in regional literature and databases.

If reliable regional estimates of in situ stress are not available, the horizontal components of in situ stress should be established by hydraulic fracturing tests performed in the non-salt units. Hydraulic fracturing for stress determination, also referred to as hydrofracturing or minifrac tests, shall be performed and interpreted with a procedure that meets or exceeds the method specified by ASTM D4645.

5.5 Assessment of Cavern Stability and Geomechanical Performance

5.5.1 General

The structural stability and geomechanical performance of liquid hydrocarbon storage caverns in salt may be assessed using numerical models that represent the geometries of the caverns, their development history and operating conditions during liquid hydrocarbon storage, the geologic structure around the caverns, the mechanical properties of the salt and non-salt units, and the preexisting in situ conditions. In particular, the numerical models may accurately simulate the time-dependent creep deformation that is distinctive of rock salt and other evaporites.

The objective of the numerical simulations is to determine boundary conditions that control the structural stability and mechanical integrity of the caverns within their particular geologic setting. These boundary conditions may include:

- cavern shape and size,
- cavern proximity to other caverns and edge of salt,
- subsidence
- key depths, and
- cavern operating pressures.

5.5.2 Cavern Shape and Size

Cavern size should be established to provide the needed storage capacity while considering the safe operating pressures for the cavern. Sharp corners or ledges produce stress concentrations and should be avoided by designing an arched roof and smooth cavern shoulders and walls. Once a desired cavern size and shape is established, numerical modeling should be used to investigate areas known to create concentrated stresses.

5.5.3 Cavern Proximity to Other Caverns and Edge of Salt

Geomechanical modeling should be used to determine safe cavern spacing. Cavern spacing should be modeled to provide adequate salt thickness between the cavern and existing or planned additional caverns, and between the cavern and the edge of the salt stock. The modeling should include expected operating pressure scenarios in the liquid hydrocarbon storage caverns, as well as in adjacent caverns.

Industry experience has shown that acceptable salt pillar widths depend on a number of factors, including consideration of storage pressures in the adjacent caverns. Distance from the edge of the salt stock should be evaluated when planning the size and location of the cavern. The level of confidence in determining the edge of the salt stock is dependent upon the quality of the available data. Additionally, there can be a higher potential for degraded salt properties and impurities near the edge of the salt, which can result in higher shear stresses and the possibility of preferential solutioning.

5.5.4 Key Depths Determination

The cemented casing should be set at a depth below the top of the salt that provides for the structural integrity of the casing and the cement bond. The salt interval provides the environment for a good pipe-cement salt bond and enhances the integrity of the casing seat for liquid hydrocarbon storage operations.