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, 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 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 down to the cavern and facilities having significant impact to safety and integrity of the cavern system.

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 which are mechanically mined, or depleted hydrocarbon or aquifer underground gas storage systems.

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 shut downs 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.
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
Space between two lengths or strings of concentric pipe or between pipe and borehole.

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

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

3.1.4 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.

3.1.5 borehole
Shaft bored or drilled into the ground either vertically or horizontally.

3.1.6 bradenhead
starting head
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.

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

3.1.8 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.

3.1.9 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.

3.1.10 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.

3.1.11 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.

3.1.12 casing, conductor
Relatively short length of large diameter steel pipe use to prevent the borehole from caving during the initial drilling of a well.

3.1.13 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.

3.1.14 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.

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

3.1.16 casing seat
Location or position of the bottom or lowermost position of a casing.

3.1.17 casing shoe
Piece of equipment threaded or welded onto the bottom joint of a casing to facilitate the lowering of the casing into the borehole.

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

3.1.19 cavern
Underground void developed by the solution mining of a salt formation.

3.1.20  
cavern chimney  
The initial section of the cavern in early development which becomes the main cavern interval during the solution mining process.

3.1.21  
cavern field  
Group of caverns within a salt dome or bedded salt formation.

3.1.22  
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.

3.1.23  
cavern roof  
Uppermost part of the cavern being just below the neck of the wellbore. The shape of a salt cavern roof may be flat or domed.

3.1.24  
cavern system  
Cavern, wellbore, casings, and wellhead.

3.1.25  
cementing  
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.

3.1.26  
circulation, direct  
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.

3.1.27  
circulation, reverse  
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.

3.1.28  
collapse pressure  
Pressure that, when applied to the exterior of a casing or tubing, causes it to collapse or fail.

3.1.29  
core, slabbed  
Core that is cut parallel to the core axis for analysis of grain structure.

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 diameter) taken during drilling, or sidewall cores (generally less than 1” in diameter) taken after a hole has been drilled.

3.1.31  
creep  
The property of salt to flow slowly and deform permanently under the influence of shear stress.

3.1.32  
creep closure
Reduction in size of a cavern due to the natural flow of salt under lithostatic, tectonic, or overburden pressures.

3.1.33
dilution string
A dilution string is a small diameter hanging string installed inside the inner most brine string. The dilution string is used to inject fresh water into the brine string at one or more locations to remove or prevent formation of salt build-up in the brine string.

3.1.34
domal salt
salt dome
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.

3.1.35
dry drilling
Drilling without significant fluid returns to the mud system at the surface.

3.1.36
emergency shutdown valve
Automated valve designed to stop the flow of liquid upon detection of specific events.

3.1.37
fire detector
A device capable of detecting the presence of a flame or the heat from a fire.

3.1.38
formation
Body of rock forming a separate and identifiable geological unit based on the rock characteristics.

3.1.39
hanging string
String of steel casing hung from the wellhead and inside the production casing and is not cemented. Casing whose weight is supported at the wellhead and hangs vertically in a larger cemented casing or another larger hanging string.

3.1.40
hole section
A section of the overall cavern well borehole.

3.1.41
hydrate
Crystalline solid made of a varying mixture of ice and gaseous hydrocarbons.

3.1.42
hydraulic communication
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
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 the escape of vapor through a small opening.

3.1.47
**lithology**
The physical character of a rock.

3.1.48
**log**
Recording of a variety of subsurface properties made by lowering detectors into the well or cavern.

3.1.49
**mechanical integrity test (MIT)**
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 mining 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, 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**
**web thickness**
Salt mass separating caverns and providing structural support to the cavern field.

3.1.57
**plugged and abandoned well**
Well whose use has been permanently discontinued and filled with material and cement.

3.1.58
**pressure gradient**
Pressure at a given depth divided by the depth.
3.1.59  
**pressure gradient, fracture**  
**fracture gradient**  
Pressure gradient which initiates fracture in the rock at the surface of a wellbore.

3.1.60  
**pressure gradient, operating**  
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**  
Core that is crushed during coring.

3.1.65  
**rubble, floor**  
Collapsed, non-soluble beds within the salt structure having fallen to the floor of the cavern.

3.1.66  
**safety strings**  
A safety string is 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**  
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 the 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
Total cavern volume as determined by a sonar survey.

3.1.76 total liquid hydrocarbon storage capacity
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 used during solution mining for water or brine flow and during product filling for brine removal.

3.1.78 turn
Withdrawal and injection 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 weephole
A small opening or openings near the end of the brine string that helps to detect an eminent overfill by allowing product to enter the brine string and be detected prior to completely filling the cavern.

3.1.81 well
The cased hole created to provide access to an underground cavern.

3.1.82 wellhead
Assemblage of base plates, spools, crosses, valves and other equipment placed on to the surface casing to control well flow.

3.1.83 working capacity
Volume of liquid that can be injected or withdrawn from the 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** blow-out 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
Storage of products in solution-mined salt caverns has been utilized in the United States since the late 1940s. Today, storage of hydrocarbon liquids and liquefied petroleum gases in caverns developed in both domal and bedded salt formations is utilized throughout the world.
Salt caverns can act independently 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 shut downs occur or to "float" on pipelines to optimize operations.

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. Product is withdrawn from the cavern by displacing it with brine or water.

### 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 are based on the time required to design, permit, and drill the cavern well, and to solution mine, and 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 is 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 creating 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 which 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.
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 United States that have suitable salt formations [1]. 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:

— The liquid hydrocarbon storage caverns should be 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 should be sufficiently remote from the property boundary and adjacent caverns.
— The liquid hydrocarbon storage caverns should be sufficiently remote from the top of salt and base of salt to ensure liquid hydrocarbon containment.

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 ten 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 formation permeability and porosity as well as other subsurface conditions, such as initial formation pressure, fracture gradient, proximity to faulting and formation thickness.

NOTE In the US, the 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 dataset. This additional data are most commonly obtained by drilling exploration wells and/or acquisition of 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 groundwater wells in a 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: 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 particular 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: 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 circulations 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 also provide direct permeability data 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 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 than too little. This is especially true for liquid hydrocarbon storage caverns whose operating pressure range is determined by geomechanical modeling that relies upon core testing. Poor sampling or insufficient core can result in skewed test results that could detrimentally impact the cavern operating conditions.

Salt core should be 4 inch 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 very 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 at a later date.

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 in observing the details of the rock. Non-salt core testing can often be done on plug samples or subcores as long as they are at least 1 ⅞ inches in diameter (see 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 upon 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 5.4. Individual core pieces selected for testing should be at least one foot in length except for those selected for Brazilian indirect tension testing (see 5.4.2.4), which can be as short as four 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 be avoided 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 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 to 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
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 non-proprietary, 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:

- 2D and 3D 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 2D and 3D 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 United States. Because of the limitations of data coverage in two dimensions, 2D seismic is considered less useful than 3D seismic in geologically complex areas because 3D seismic provides complete coverage of the survey area. 3D 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 2D and 3D seismic surveys usually need long offsets to image near vertical edges and steeply dipping strata. Multiple 2D seismic lines are often acquired in radial patterns to image the edge of salt. For steeply dipping and structurally complex structures, 2D 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. All of 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 2D and 3D 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 ultrahigh-frequency radio waves. Borehole radar has been used in Europe in a similar fashion to VSPs, but tool availability may be limited in the United States.

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 2D and 3D 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 particular 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 towards 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 basemap 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 isopachs 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 including 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 Geologic Site Characterization

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 operations\(^1\). The stresses in

\(^1\) Liquid hydrocarbon storage caverns typically exhibit an apparent increase in cavern volume owing to the incremental associated with slightly under-saturated product displacement brine.
salt redistribute as it creeps; if there are non-salt units near the creeping salt, loads transferred from the salt typically accumulates 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. Generally speaking, 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:

- 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 Practice D3740 [2] are considered capable of competent and objective testing, although compliance with Practice D3740 does not in itself assure reliable testing. Reliable testing depends on many factors, and Practice 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, and 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 a specimen shall have a length-to-diameter ratio of 2.0 to 2.5 and a diameter of not less than 1 ⅞ inches. In addition, it is desirable that the diameter be at least ten times the size of the largest mineral grain. The grain size of non-salt rock generally is small enough that 2 inch diameter specimens typically satisfy this recommendation. For salt, a specimen
diameter of nominally 4 inches 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 3,000 psi has been demonstrated to mitigate or heal preexisting specimen damage, yielding more repeatable and somewhat higher dilation strengths in triaxial compression tests [3].

5.4.2.4 Brazilian Indirect Tension Tests

By definition, 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.

Brazilian indirect tension tests 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.

Triaxial compression tests shall be performed and interpreted with a procedure that meets or exceeds the method specified by ASTM D7012. This standard 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.

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 Standard D7012 for rocks like 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.

ASTM Standard 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.

NOTE For triaxial compression tests on salt, Mellegard and Pfeifle [4] 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 Standard 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.

5.4.2.5.3 Elastic Moduli and Dilation Strength of Salt

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. Standard 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.

ASTM Standard 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.

5.4.2.6 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 for comparing different salts and variations in salt response from one location to another.

Triaxial creep tests 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 [5] 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 conditions [6].

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 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.

Design depths for wellbore casings and for cavern roof and bottom are influenced by the following factors:

- top of salt depth,
- design maximum pressure,
- design cavern diameter and height, and
- insoluble settlement.

Analysis of overburden density logs and fracture gradient testing should also be used in the cavern design. These studies will help determine the safe operating pressures in the cavern.

The cavern diameter should be determined by estimating the spacing between adjacent caverns and proximity to the edge of the salt dome and facility property boundaries. Cavern height should be determined by estimating the design storage capacities and the cavern diameter.

Estimates of insoluble percentage in the salt mass should be determined from core samples and open-
hole well logs acquired during the drilling phase. Insoluble impurities, usually anhydrite, are present in most salt masses and the bulk volume of these insolubles upon settlement will be greater than their original volume, at times as much as 30% to 40% greater. During planning of the total drilling depth for the cavern, the expected volume of insoluble settlement in the lowest portion of the cavern, known as the sump, should be estimated because several hundred feet of the initial cavern space can be lost during the solution mining process.

Salt creep rates and surface injection pressures are constraints that should be estimated for determination of total cavern depth. Salt creep rates increase with depth due to increasing in situ stress and temperature. Pressures for water injection during solution mining increase as cavern depth increases, affecting the design and cost of associated surface facilities.

5.5.5 Wellbore and Cavern Roof Design Considerations

The distance from the bottom of the cemented casing to the cavern roof should be sufficient to prevent roof strains from affecting the integrity of the cemented casing and casing connections. Geomechanical modeling should be used to evaluate the effects of the salt creep in this interval. Proper design of the uncased wellbore section and the cavern roof mitigates the stress and creep strain placed on the casing seat and casing connections, reducing the risk of casing damage or loss of integrity in the cement bond at the casing seat.

5.5.6 Storage Pressures

Maximum pressure should be determined by evaluating the fracture gradient of the salt stock and the design depth of the casing seat with an applied safety factor.

5.5.7 Surface Subsidence

Where applicable, geomechanical modeling should be used to provide a prediction of the expected rate of surface subsidence based on:

- Depth, spacing, height, and volume of the cavern and adjacent caverns.
- Geomechanical properties of the salt and non-salt units above and surrounding the caverns.

6 Cavern and Well Design

6.1 General

In designing salt caverns for hydrocarbon storage, consider the cavern’s salt formation geometry, the cavern operating pressures, the in-situ stress state, and the salt’s properties (and in some cases the mechanical properties of the overburden layer) to reduce susceptibility to possible cavern failures. The following failures shall be prevented:

a) Fracturing the formation or casing seat by cavern operating pressures.

b) Loss of volume due to abnormal cavern closure.

c) Cavern roof collapse or sidewall slabbing with hazards to casing strings and the potential for surface subsidence.

d) Washout to the edge of the salt formation.

e) Unplanned coalescing of adjacent caverns.

Design of the storage well system shall ensure the confinement of the stored liquid to the cavern system (see Figure 1).

Major components of well design include:

- hole section design,
- locale,
- well spacing,
- cavern depth,
— cavern diameter,
— cavern volume,
— casing design, and
— wellhead design.

6.1.1 Setting Cavern Depth

The roof of the cavern shall be established deep enough to accomplish the following.

a) Having sufficient salt back to ensure adequate roof support of the overburden.

b) In bedded formations, the strength of an impervious, overburden layer may be used to provide roof support.

c) In domal formations, the cemented production string should be deep enough to adequately seal in the salt below the caprock. The recommended depth of the production string is a minimum of 300 feet below the top of the salt. The cavern roof should be below the casing seat.

d) The production casing seat depth shall be set so that the maximum cavern operating pressure does not exceed the formation fracture gradient or as limited by regulation.

The cavern bottom should not be set excessively deep because temperature increases with depth. As temperature increases, so do salt-creep rates and, therefore, closure rates. With displacement caverns, depth also increases the pressure required to inject into the cavern.

6.1.2 Cavern Shape Considerations

Theoretically, a spherical cavern is the most stable cavern shape. An inverted cone shape and arched roof is generally considered an acceptable alternative. While the arched shape of the roof is preferred, flat roof caverns can be designed to have adequate strength and integrity.

In designing and solution-mining the roof, care must be taken to prevent attics that may trap product. Shaping and control of the roof is generally achieved through control of the blanketing material fluid level during cavern formation.

In designing the cavern, develop space below the brine string to permit accumulation of insolubles, both from initial and operational solution-mining activities.

6.2 Cavern Spacing Constraints

6.2.1 Optimum Salt Formation Utilization

Suitable salt formations located in logistically important areas represent an extremely valuable resource whose use should be optimized.

The designer should consider a master plan for a facility before the first cavern is designed.

6.2.2 Structural Integrity Concerns

6.2.2.1 Common Ratios for Cavern Spacing

There are two commonly used ratios used to help develop appropriate spaces between caverns in a field, P/D and S/D. These ratios may be reduced where geomechanical studies show that the cavern stability shall not be affected. These studies shall take into account:

(a) geological information determined from geological studies;

(b) cavern shape and roof configuration;

(c) change in cavern shape and volume over the operating life of the facility due to mining by undersaturated brine or salt creep; and

(d) operating practices, including maximum and minimum operating pressures, rate of pressure changes, and inventory practices of adjacent caverns.
The designer should consider the effects of operational solution mining over the life of the facility in determining spacing ratios. The recommended approach is to use the final theoretical solution-mined diameter at the end operating life of the facility in determining $D$.

### 6.2.2.1 P/D (Pillar Distance)

The distance between two adjacent solution-mined caverns in the formation should be such that the ratio $P:D$ is not less than 1:1 for brine displacement caverns, where $P$ equals the distance between the two cavern boundaries and $D$ equals the average of the maximum diameter of the two caverns.

### 6.2.2.1.2 S/D (Separation Distance)

The distance between two adjacent solution-mined caverns in the formation should be such that the ratio $S:D$ is not less than 2:1 for brine displacement caverns, where $S$ equals the distance between the centers of the two caverns and $D$ equals the average of the maximum diameter of the two caverns.

### 6.2.2.2 Creep Closure

Increasing the density of caverns in a formation decreases the salt web area while increasing the differential stress in the salt formation. The differential stresses result from the difference between the in-situ pressure of the overburden on the web and the operating pressure of the open cavern. When these stresses exceed the octahedral shear strength of the salt, visco-plastic or elastic creep starts, resulting in lost cavern volume over time. If a cavern field is not properly designed, the salt creep can lead to both capacity loss and surface subsidence, which can cause excessive stresses on cemented casings in the immediate area and adversely impact safety, property, and the environment.

Proper analysis of the design of a cavern field involves the following:

a) assessment of the in-situ lateral stresses;

b) the range of operating pressures in the cavern;

c) the structural properties of the salt over the full height of the caverns;

d) in bedded formations, the properties of the overburden rock layer in the stress field.

This analysis should be performed by engineers or geologists experienced in such work to determine the proper separation of caverns to prevent closure rates in excess of acceptable limits.

### 6.2.2.3 Coalescing Caverns

Care should be taken to prevent adjacent caverns from solution mining into one another to the point that the web thickness is no longer adequate to prevent fluid from the higher pressure cavern from flowing into the lower pressure cavern. Coalescing caverns can also lead to greater subsidence risk.

### 6.2.2.4 Salt Boundary Constraints

The properties of the salt formation may vary near the flanks of domal formation, and the salt may be more fractured or have inclusions not typical of the rest of the dome. The shape and location of the flanks may be difficult to determine because of the potential for overhangs and other anomalies. Caverns solution mined within 500 ft (approximately 150 m) of a domal flank should be carefully analyzed with additional core samples and side scan seismic mapping.

Bedded salt formations may vary due to salt thinning, stratigraphic changes, or dissolution zones. These variances should be considered in the cavern’s design.

### 6.2.3 Property Limit Setbacks

Salt caverns in a salt formation interact and effect nearby caverns, regardless of ownership. Joint industry development plans may be required in maturing cavern fields to properly and safely develop the salt underlying the property boundaries. In the absence of agreement between adjacent property owners, wellheads should not be placed closer to any other cavern in the formation than twice the sum of the diameters of existing and planned caverns. Wellheads and cavern walls should be no closer than 100 ft
(approximately 30 m) from the property line.
Some regulations require certain setbacks and should be adhered to.

Figure 1—Typical Cemented Casing Program for Domal Salt

6.3 Hole Section Design

6.3.1 General

A hole section is a vertical length of the well having a discrete function in the cavern system. Design of each hole section should consider the diameter and depth needed to allow for the installation of the final
cemented production casing.

Typically, the progression by depth and diameter of hole sections is:
a) conductor casing hole section;
b) surface casing hole section;
c) intermediate casing hole section(s);
d) production casing hole section;
e) cavern hole section.

6.3.2 Conductor Casing Hole Section
The conductor casing hole section is the first section to be developed and shall be lined by the conductor casing.

Conductor casing or drive pipe is used as the foundation for the well and the prevention of near-surface soils from caving into the wellbore and undermining the drilling rig.

The setting depth of this string is dependent on the competency of near-surface formations.

6.3.3 Surface Casing Hole Section
The surface casing hole section functions to isolate the lower portion(s) of the wellbore from the underground sources of drinking water (USDW).

Setting depth is determined by the depth of the lowest USDW and should be confirmed by the use of an open-hole resistivity log.

6.3.4 Intermediate Casing Hole Section(s)
When drilling out below the surface casing, zones that lead to drilling problems may be encountered including unstable or unconsolidated zones, lost circulation zones, and pressurized production zones. The intermediate casing hole sections function to isolate these problem zones, enabling the deepening of the well.

Use of a contingent intermediate casing string above the salt should be evaluated if severe loss of circulation is anticipated.

NOTE The conductor and surface casing sections are often sized in order to allow for a contingency casing string to be set.

In domal salt wells, two casing strings shall be set into the salt. These casing strings are the last intermediate casing and the production casing strings. Experience has shown that setting the intermediate casing 150 ft to 200 ft into the salt may be necessary for isolation of the cap rock.

Two intermediate casing strings should be set across any known corrosive zones.

6.3.5 Production Casing Hole Section
The production casing hole section is drilled to allow the running, setting, and cementing of the production casing which is the final cemented casing string in the well.

The setting depth of the production casing is influenced by the need for adequate saltback distance.

Often the setting depth is determined by pressure considerations at the casing seat for future liquid storage operations.

The production casing should be set in a section of salt determined competent to provide a pressure-containing casing seat.

In bedded salt, the casing seat should be within the cavern salt or an overlying salt bed.

6.3.6 Cavern Hole Section
The cavern hole section is below the final cemented production casing and includes the cavern neck,
cavern interval, and sump.

6.4 Casing Design

6.4.1 General
Casing is used to maintain borehole stability, prevent contamination of subsurface formations and control pressures during drilling, mining and liquid hydrocarbon storage operations. Casing also provides points of attachment for the wellhead and blowout prevention equipment.

6.4.2 Design Considerations
In most wells, the casing design includes conductor pipe, surface casing, and production casing. In many wells, one or more strings or intermediate casing will be used. In some cases, the designer should consider designing the intermediate casing or surface casing to withstand full product pressure or installing a pressure control system on the annuli. This would minimize problems that could result from leaks or failure in the production casing.

Each section of casing should be designed with consideration to the physical forces acting on it. Physical forces include the loads acting to collapse, burst, compress or pull apart (axial compression and tension). Forces acting on the casing change over time from when the casing is cemented, solution-mined, placed in liquid hydrocarbon storage operations, and throughout the service life of the well. Once the ranges of physical forces are determined, the worst-case set of conditions should be designed for. Safety factors should be applied to design calculations to provide a level of additional margin of mechanical strength.

Diameters should be chosen which allow for adequate space between the outer and inner strings for successful cement jobs. Because the space between the outside of the casing and the wellbore wall is cemented, sufficient annular area is required for the cement to adequately fill and ultimately seal-off this space. Experience in running and cementing large diameter casings has shown that a hole diameter six inches greater than the diameter of the next inner casing is an optimum annuli; for example, 20 in. casing should be set in a 26 in. hole, where feasible.

The casing strings are often larger in domal salt wells than in bedded salt wells and may require the use of line pipe in lieu of oil country tubular goods (OCTG) casing. Differences between line pipe and OCTG should be taken into consideration, including:

- different ovality tolerances;
- different metallurgy;
- different connection methods; and
- applicability of casing design equations for large outside diameter (OD) line pipe.

All casing should be cemented in-place from the bottom of the casing to the surface.

All casing should be supplied with Material Test Reports which should be kept for the life of the well.

NOTE Hanging string design is addressed in 8.3.8.

6.4.3 Conductor Casing or Drive Pipe
The conductor or structural pipe is set to shut off unconsolidated shallow formations and may or may not be cemented. In many hard rock areas, conductor casing may not be required.

The conductor casing, typically line pipe, is either driven into the ground to refusal or is drilled with an auger, set in-place, and cemented.

If driven, collapse design shall be calculated to withstand lithostatic pressure at the anticipated setting depth and the maximum buckling forces expected during pipe driving. A reinforced drive shoe may be used. If driven, the pipe is not cemented.

If augured, collapse design shall be calculated to withstand the differential pressures encountered during cementing.

Burst and tensile loads are generally not factors due to the typically shallow setting depths.
6.4.4 Surface Casing

The surface casing is designed to protect all fresh-water zones. In some specific areas, regulatory agency rules and regulations allow production casing to also serve as surface casing. Also, in some wells the surface casing may not be set deep enough to cover all fresh-water zones, and an additional casing string may be used for that purpose.

The surface casing shall be cemented from the bottom of the casing to the surface. If the surface casing is set into the salt, salt-saturated pozzolan or equivalent cementing materials shall be used. If the surface casing is set above the salt, a fresh-water pozzolan or equivalent cementing mix may be used.

Collapse design shall be calculated to withstand the pressures encountered during cementing of the surface casing.

If encountering a gas-bearing formation is anticipated during the drilling of the intermediate hole section, burst design shall consider the expected gas pressure.

Due to the usual shallow setting depths of the surface casing in domal salt, compressive and tensile loads are generally not a factor.

In bedded salt well design, there may not be an intermediate casing and the Bradenhead is installed on the surface casing. In this case, burst design for the top of the surface casing shall be based on maximum operating pressure without allowance for pressure containment due to cement sheath or hydrostatic head outside of the surface casing. Burst design for the bottom of the surface casing shall be based on the cementing differential pressures to be encountered. Since the production casing and the solution mining hanging string loads are exerted on the surface casing, maximum compressive loads shall be used.

6.4.5 Intermediate Casing

One or more intermediate casing strings are sometimes needed for well completion and is recommended in those cases where it will improve long-term cavern integrity (such as providing two cemented casing strings through a caprock interval). The amount of cement used is based on the well design and locale, but, if practical, enough cementing material shall be used to bring cement up into the surface casing.

In domal salt well design, the intermediate casing’s main function is to bridge the hole sections through the unconsolidated overburden, the caprock, and into the top of the salt. Drilling issues may require multiple intermediate casings.

Two intermediate casing strings should be set across any known corrosive zones.

The Bradenhead is typically installed on the last intermediate casing, which allows for the setting of the production casing and the remainder of the wellhead.

Collapse design shall be calculated using intermediate casing cementing pressures.

Burst design should be calculated differently for the top and bottom sections of the last intermediate casing string. Burst design for the top of the intermediate casing string shall be based on maximum operating pressure without allowance for pressure containment due to cement sheath or hydrostatic head outside of the intermediate casing. Burst design for the bottom of the intermediate casing string shall be based, at a minimum, on the cementing differential pressures to be encountered.

During the cementing of the production casing, cement at the surface could settle down the annulus, causing an open annular area between the casings. During liquid operations, liquid could pass through the wellhead seals into the void space created by cement settlement. Experience indicates that welding the upper 200 ft to 400 ft of intermediate casing can eliminate liquid leakage through threaded casing connections.

Welding and inspection procedures shall be developed with consideration for wall thickness and grade. Welded connections should be inspected using a non-destructive test method.

6.4.6 Production Casing

The production casing shall have adequate tensile and collapse strength for the setting depth. When practical, it should be cemented to the surface with salt-saturated cementing materials. In salt domes,
casing should be set at least 300 ft within the salt or as regulations provide.

In bedded salt formations, the production casing is typically set into the salt. If the production casing is set above the top of the salt, the rock forming the cavern roof shall be nonporous, impermeable, and of sufficient strength to serve as the cavern roof.

The production casing shall be pressure tested before drilling out the plug (shoe). Incomplete cement bonding can occur if the pressure test is made after cement has started to set but has not yet developed enough compressive strength to withstand the test pressure. The casing test pressure shall be the higher of either that pressure required by regulations or 125 % of the designed working pressure but not exceed 100 % of the minimum yield pressure of the casing. The test pressure should be maintained for a minimum of 30 minutes, or longer if required by government regulations.

The casing seat and cement of the production casing shall be pressure tested after drilling out. At least 10 ft of salt below the casing shoe shall be penetrated prior to the test. The test pressure calculated at the casing seat, as a minimum, shall be the maximum operating pressure at that point. The maximum operating pressure will depend on area, depth, well, and salt characteristics and may vary widely.

Collapse design should be based on full lithostatic load externally and atmospheric pressure internally. Burst design shall be calculated using the maximum operating pressure and/or MIT pressure without allowance for pressure containment due to cement sheath or hydrostatic head outside of the production casing.

If a casing string of varying wall thicknesses is called for, one joint of the smallest internal diameter pipe should be run as the last (shallowest) joint in the hole. This prevents tools or equipment from being run and stuck downhole in the smaller ID pipe.

If the final casing is welded, welding and inspection procedures shall be developed with consideration for wall thickness and grade. Welded connections should be inspected using a non-destructive test method.

### 6.4.7 Product String (Blanket String)

An additional uncemented casing string is sometimes suspended inside the production casing. This string serves a purpose similar to the production casing. It is used if high corrosion rates are expected or if it is desirable to remove the inner-most casing string and the brine string for inspection. The blanket string results in no flow occurring on the production casing. The production casing should always have a static blanket of product between it and the product (blanket) casing.

### 6.4.8 Safety String

A safety string may be considered based upon the cavern’s operations, the stored product’s characteristics, and the cavern’s location. The safety string is terminated at a sufficient height above the brine string's lowest setting such that, during cavern filling operations, product would enter the safety string before it would return to the surface through the brine string. A high pressure switch monitoring the safety string’s pressure can serve to close the wellhead emergency shutdown valves prior to well overfill. The safety string should be kept filled with fresh water and periodically flushed to prevent brine entry and possible plugging due to salt deposition. Brine entry could negate the safety string’s pressure-sensing role.

A safety string may also be a packer on pipe installation between the hanging brine string and the production casing. The safety string would be hung off in the surface wellhead and the packer would be set near the end of the production casing. This installation would act as an additional barrier to the cemented production casing. The annular space between the safety string/packer would be monitored for pressure and an alarm could be used to alert operators to an issue.

### 6.5 Wellhead Design

#### 6.5.1 General

The wellhead is used to contain the liquid hydrocarbon stored in the cavern system and to allow
controlled flow into and out of the cavern system.

6.5.2 Design Considerations

Two separate wellheads are typically used during the service life of a cavern system: one for solution mining development, one for liquid hydrocarbon storage service.

All wellhead components shall be steel of sufficient strength to withstand the maximum operating pressure. Safety factors should be applied to design calculations to provide a level of additional margin of mechanical strength.

Appropriate materials for the service and temperature range to be encountered shall be selected for wellhead components and seals.

Outlets shall be sized for anticipated flow rates.

Ring type joint flange connections shall be used as opposed to raised face flange connections. On ring type joint connection between flange faces, stainless steel ring gaskets should be used and should be replaced after each use.

6.5.3 Wellhead Considerations for Solution Mining Service

The solution mining wellhead is installed during the completion of well drilling and remains in place through the end of cavern solution mining operations (see Figure 3).
The solution mining wellhead should be designed to allow the injection of pressured raw water from the surface, down the well, and into the salt formation for salt dissolution and return of the brine solution to the surface for processing or disposal. The solution mining wellhead equipment is also designed to allow for injection of a roof protection blanket into the production casing annulus.

The design of the wellhead should take into account site-specific considerations, such as brine and corrosive gases. The equipment should have internal coatings to resist corrosion or adequate corrosion allowances during solution mining operations.

6.5.4 Wellhead Considerations for Liquid Hydrocarbon Storage Service

The storage wellhead is installed after the completion of solution mining and cavern development activities and prior to the commissioning MIT (see Figure 4).
6.5.5 Bradenhead

The Bradenhead, also known as the starting head, is typically welded in the field to the last intermediate casing or the surface casing where no intermediate casing is present and is the foundation for the remaining wellhead equipment.

The size of the Bradenhead is determined by the size of the last two cemented casing strings.

The Bradenhead should have two side outlets and be sized to allow adequate flow rate of returns during the cementing of the last cemented string.

Slip-on welded type Bradenheads should be used. This weld should be made under controlled fabrication shop conditions where the weld can be gas tested.

Welding and inspection procedures shall be developed with consideration to wall thickness and grade of the pipe being welded.

The welded connection shall be X-ray inspected or the equivalent.

6.5.6 Casing Hanger for Casing Strings

A slip-type casing hanger should be used to hang off the production string in the Bradenhead. The casing hanger shall be designed to fit in the bowl of the Bradenhead and fully close around the OD of the production casing. The hanger shall be designed to support the entire weight of the casing string and should have a compressed, energized, elastomeric seal that is compatible with the product to be stored.
6.5.7 Double Studded Adapter Pack-Off Flange

If the Bradenhead flange has a lower pressure rating than the wellhead components above it, a double studded adapter pack-off flange shall be used to transition pressure ratings between the Bradenhead flange and the bottom flange of the casing spool immediately above it.

The double studded adapter pack-off flange should have studded, flanged connections with ring joint gaskets adapting to the Bradenhead and the spool component immediately above it.

Double elastomeric p-seals in the double studded adapter pack-off flange should be used for a seal on the production casing stub above the slips. There should be a minimum of two ports per seal to allow for placement of packing material. Test fittings should be placed between and below the p-seals to test for adequate sealing. The seal material shall be compatible with the product to be stored and capable of sealing without excessive energizing pressure on a typical casing pipe OD.

6.5.8 Casing Spool

The wellhead may have one or more casing spools, depending on service. The casing spool allows for the landing of a hanging string and should make a seal on the casing string below.

During the solution mining process two casing spools are needed to hang the long and the short hanging strings and to allow the flow of raw water into the well and brine out. The side outlets should be sized to provide adequate flow area for the maximum flow rates at a minimal pressure drop. The bottom flange of each spool should have an elastomeric p-seal to seal around the hanger neck of the previous hanging casing, preventing hydraulic communication. Operators should consider the use of dual p-seals.

During liquid hydrocarbon storage operations there is typically only one casing spool that is needed to suspend the brine string and allow the maximum liquid flow through its side outlets and brine through the brine string.

The casing spools should be designed with a bowl to accept the mandrel casing hanger. The top flange of each casing spool should be fitted with lock down pins that help activate the mandrel hanger body seal and hold the mandrel hanger in place.

6.5.9 Casing Hanger for Hanging Strings

Casing hangers designed for solution mining and liquid hydrocarbon cavern operations are typically of the mandrel type. A mandrel hanger has a solid body with a through-bore ID the same as the attached tubing or casing. The mandrel hanger is designed to withstand the tensile loading of the attached hanging string. The mandrel hanger generally has elastomeric seals on the OD of the hanger that seals against the hanger bowl. The mandrel hanger neck should be sized for the elastomeric p-seal of the flange immediately above.

6.5.10 Flow Cross/Flow Tee

The section above the top casing spool can be a four-way fitting (flow cross) or a three-way fitting (flow tee). The outlets should be sized to allow adequate flow area for the maximum flow rates at a minimal pressure drop.

6.5.11 Manual Wellhead Valves

Manual solution mining valves shall be placed directly on the side outlets of the various casing spools of the wellhead and are used during cavern development operations. These valves are designed to allow high pressure raw water to be injected into the salt formation and brine to be displaced to the surface. Valves of suitable pressure rating shall be installed for safe injection and removal of blanket materials, and are designed to safely operate at solution mining pumping pressures as well as blanket containment pressures. In addition to the rated working pressure of wellhead valves, appropriate materials for the service to be encountered should be selected for valve bodies, trim, and seals.

Manual liquid hydrocarbon storage valves shall be placed directly on the storage wellhead during the liquid storage conversion workover. There should be no outlets, regardless of size, or spools/spacers between the manual valve and the wellhead outlet flange. These valves are designed to allow for the injection and withdrawal of high pressure liquid used during storage operations. In addition to the rated
working pressure of wellhead valves, appropriate materials for the service to be encountered should be selected for valve bodies, trim, and seals. See 9.4.2 for ESD equipment.

A crown or logging valve should be installed on top of the upper flow cross. Future operations through this valve, such as logging and snubbing, should be considered when sizing this valve.

6.6 Storage Volume

6.6.1 General

Setting the required cavern volume should be based on the overall logistics plan for the stored product, including provisions for fluctuating demand and supply or transportation delays or restrictions. Storage cavern capacity normally is stated on a volumetric basis, such as barrels.

6.6.2 Displacement-fluid Handling Facilities

Salt caverns require displacement-fluid handling facilities. The working capacity of the cavern should be sized to match a combination of brine storage, a brine disposal system, and/or a displacement-fluid sourcing system.

6.6.3 Compressible Fluids

With highly compressible fluids where density varies with pressure and temperature, consideration should be given to using a design based on mass. Where the storage pressure greatly affects the storage density (as with ethylene), cavern depth will greatly affect the mass storage capacity of a cavern for a given volume.

6.6.4 Intentional Operational Solution-mining

Cavern volume can be deliberately solution mined while operating as a storage facility. One such method would be to initially solution mine a cavern to partial size, enabling product storage in the top of the cavern. Solution-mining tubing then is positioned to solution mine the bottom of the cavern to the desired shape and volume, with the stored product acting as a blanketing material. Another method would be to use fresh water as the displacement fluid until the desired cavern configuration is achieved. Both methods require carefully designed and controlled solution-mining programs to produce the desired cavern geometry.

6.6.5 Traps (Attics)

Care should be taken during solution mining to avoid the creation of traps (or cavity space) above the production casing string or in the cavern interval. During storage operations, such space fills with product, which cannot be recovered. An insoluble hydrocarbon blanketing material or inert gas such as nitrogen should be used during the solution-mining phase to minimize attic creation.

6.6.6 Cavern Dynamics

Cavern size will change over time due to two opposing processes: creep closure and operational solution mining. As discussed in Section 8, the formation of a cavern creates stresses in the salt formation causing creep of the salt to close the hole. This effect increases with greater depths (due largely to increased temperature) and with lower cavern operating pressures (relative to the in-situ pressure of the formation).

At the same time, displacement caverns continue to solution mine new space due to less than saturated brine and due to the introduction of free water in some stored products.

6.7 Displacement-fluid Characteristics

6.7.1 Saturation

The displacement fluid will normally have a greater density than the product being stored. The common fluid material density of aqueous sodium chloride salt solutions varies from fresh water to totally saturated brine. The degree of saturation (density or gravity) will affect the hydraulics and operational solution-mining rate and is the most important displacement-fluid property to be considered during design.
6.7.2 Fluid Corrosivity
Displacement fluids may contain atmospheric gases, primarily oxygen ($O_2$) and nitrogen ($N_2$). High $O_2$ concentrations affect the corrosion rates on tubing strings and other elements of the system. Where $O_2$ concentrations are high, consider deoxygenating the brine, special metallurgy, or coatings. Also, where high-purity olefins are to be stored and $O_2$ and $N_2$ concentrations were high in the fresh water used to solution mine the cavern, the brine remaining in the cavern after solution mining should be removed and deoxygenated prior to introducing product.

6.7.3 Rainwater
Atmospheric pits are commonly used to store brine. These pits collect rainwater that reduces the level of brine saturation. The difference between the anticipated rainfall and the evaporation rate for the site, together with the surface area of the brine pit, should be considered when evaluating the effects of operational solution mining on cavern design.

6.7.4 Hydraulic Restraints
The required flow rates in and out of a storage cavern shall be identified to properly size the casing program, operating tubing strings, and brine pumps. Required operating pressure in a cavern should be known to help set the depth of the cavern. The properties of the product to be stored can influence the cavern depth and should be considered.

6.8 Product Characteristics
The stored product must be nonreactive with salt, water, or carbon steel and can be considered only slightly soluble in salt or water. Products that are self-reactive should not be stored in salt caverns.

The physical and chemical properties of the stored product must be known, including gravity, viscosity, compressibility, solubility, pressure-volume-temperature (PVT) characteristics, and stability in water. In liquid products, the volume of entrained free water must also be known.

Stored products will absorb compounds from the salt formation and/or the displacement fluid. With high-purity products, these trace materials can affect product quality. Salt dome structures differ in the nature and quantities of these contaminants (such as methane, carbon dioxide, hydrogen sulfide, and heavier hydrocarbons). These trace gases and liquids are produced into the brine and are then transferred into the product or can be directly produced from the cavern into the product. The product can also absorb contaminants, not introduced by the salt formation, from the displacement fluids. Dissolved oxygen or nitrogen from sourcing or surface storage of brine can also be transferred into the product.

7 Drilling
7.1 Preliminary Considerations
7.1.1 Permits
All necessary permits shall be obtained before drilling commences.

7.1.2 Site Layout
The main considerations for location should include rig and facility requirements, safety, environmental protection while drilling, tractor-trailer traffic flow, pipe staging, double-joint welding and NDE space, and subsequently operating the site. Emergency and pollution control measures should be a part of the site layout plan.

7.2 Rig and Equipment
7.2.1 Rig Selection
The selection of the drilling rig shall be made in accordance to the well design tubular loads and diameters.

The rig shall have a hook load capacity sufficient to lift the casing with the largest total string weight and contingent over-pull.
The minimum rotary beam opening shall be based on the diameter of the largest non-conductor casing.

The rig floor height above ground level shall provide enough clearance for the stack-up of the above ground casing, Bradenhead, temporary adapter/cementing spools and blowout preventer (BOP) equipment. Also, sufficient rig floor height shall be provided to allow the make-up below the rig floor of any hole-openers having larger diameter than the rotary table.

The rig substructure should have the rotary capacity to suspend the heaviest casing string load plus (simultaneously) a rack-back capacity of supporting the maximum drill pipe and bottom hole assembly (BHA) loads.

Available drill pad area shall accommodate the drilling rig chosen for the job along with the ancillary equipment specific to that rig. A typical pad area for a large bore drilling rig is 400 feet by 300 feet. The rig provider should be consulted for the pad area required and acceptable rig layout drawings.

7.2.2 Fluid and Cuttings Handling Equipment

The rig pumps should be equipped to supply adequate pump pressure and flow rates to transport cuttings to the surface. To prevent washing out the near surface borehole, it is recommended that low flow rates along with sufficient mud viscosity be used to lift the cuttings.

Due to the volume of drill cuttings produced during large bore drilling and hole opening, proper removal of drill cuttings is essential. Removal of the cuttings prevents loading of the wellbore annulus and mitigates a possible lost circulation condition by reducing equivalent circulating density.

The minimum flow line diameter should be designed for the mud flow and volume required for proper removal of the cuttings. A typical flow line diameter is 10 in. to 12 in. In order to keep the flow line clear of cuttings, it is good practice to install a fresh water jet line into the flow line to circulate clean drilling fluid or fresh water.

The fluid handling system consists of hopper, suction tank, water tank, trip tank, gas buster, shaker tank, and choke manifold.

Multiple, cascading shale shakers should be considered. One extra shale shaker should be installed to allow for screen maintenance and redundancy. Several screen sizes are usually required for solids removal, depending on which hole section is being drilled.

Desander, desilters, mud cleaners, and centrifuges are additional solids control equipment that should be considered for removal of finer solids.

A closed loop system should be considered for the handling and disposal of the drill cuttings below the fresh and useable water zone, eliminating the need of the collection of the drill cuttings in an earthen pit or reserve pit. Cuttings should be collected in open top cuttings tanks that allow a track hoe to access the cuttings for loading into dump end trucks to haul to disposal. An auger tank can be used for loading dump end trucks instead of using a track hoe.

7.2.3 BOP System

A BOP system is a set of hydraulically operated equipment used to isolate the well while drilling in the event of an unexpected pressure event, or kick. The BOP is also used to seal the wellbore in the event no drill pipe or casing is in the well.

A BOP shall be used during drilling of the pilot hole of each hole section to maintain well control. During hole opening operations, a BOP should be used if available in sufficient size.

API 53 [7] recommends that the minimum working accumulator volume should be equal to three times the volume required to close the annular preventer and one pipe ram.

The BOP system shall be pressure tested and function tested (both high and low pressure) prior to spudding the well and periodically, while drilling, to verify integrity. Each time any pressure containment seal on the stack is disconnected, the BOP system should be pressure tested to a high and low pressure.
7.2.4 Drill Pipe, Drill Collars, and Crossovers

Drill collars give the primary weight and rigidity for the BHA. Drill collars also help maintain sufficient annular velocity of the drilling fluids and cuttings.

The drill pipe size, weight, grade, and threads shall be determined by depth of hole required, geologic formation drilled, required mud flow and drill bit/hole-opener torques.

To help avoid drill pipe or drill collar failures, inspections should be performed on a periodic basis depending on drilling conditions. When a rig arrives on location, the inspection papers of the drill pipe and drill collars should be verified.

7.2.5 Drill Bits, Hole Openers, and Under-reamers

Hole openers are used to enlarge the wellbore after the pilot hole has been drilled and logged. Because of the large volume of formation being drilled and removed with a hole opener and because of the high torque that is generated with a hole opener, consideration should be given to limiting the subsequent hole opener size to 10 in.

The torque on the BHA should be monitored. Excessive torque, due mainly to loose cutter cones, can result in a drill pipe or drilling tool failure.

To help mitigate the chance of backing off the guide from below the hole opener, the guide and the hole openers can be welded, or strapped with a piece of metal plating.

Under-reaming in the caprock should be avoided. Under-reaming in the salt section of the well is a common practice.

7.2.6 Shock Subs

Shock subs can be used in the drill string while drilling the caprock formation. Shock subs help keep the drill bit or hole opener in contact with the formation being drilled. This may reduce the produced vibration in the drill string and the surface rotary equipment.

7.2.7 Mud Motors

When maintaining a vertical hole is important, mud motors in conjunction with vertical steering devices should be used to drill the cavern salt section. Motors are not commonly used in the unconsolidated portion of the well or the caprock section.

7.3 Drilling Fluids

7.3.1 Surface Casing Hole Section

Freshwater based drilling fluid systems are typically used to drill the surface hole section.

Control of the viscosity, density and solids content is essential to prevent lost circulation, to maximize drilling rate of penetration (ROP), and to maintain overall borehole stability. Bentonite and other additives can be introduced into the make-up water to produce increased viscosity and assist with filter cake production and lifting of the drill cuttings.

7.3.2 Intermediate Casing Hole Section

Freshwater based drilling fluid can be used to drill the intermediate hole section of a storage well, until the salt formation has been reached. Due to salt dissolution and washout potential in bedded or domal salt formations, a freshwater based drilling fluid should not be used for drilling salt. Potassium chloride (KCl) or sodium chloride (NaCl) may be required to maintain the desired mud properties, as different formations are encountered.

Depending on the specific casing program of the well to be drilled, and the availability of brine, it may be desirable to convert to a salt saturated drilling fluid system prior to drilling the intermediate hole section. Otherwise, the system should be converted from freshwater based to salt saturated before encountering the salt formation. Chloride concentration should be at or near saturation to minimize dissolution of the salt and maintain a consistent borehole profile. Continued control of the viscosity, density and solids content of the drilling fluid is critical to prevent lost circulation, to maximize drilling ROP, and to maintain...
overall borehole stability.

Non-aqueous drilling fluid systems can be used in the intermediate hole section if potassium or sodium chloride inhibition is insufficient for formations encountered. If potassium chloride stringers are encountered, the non-aqueous drilling fluid system maintains borehole stability and profile by minimizing or eliminating washout of the highly soluble salt. If a formation in the intermediate hole section is sub-pressured, non-aqueous drilling fluid may be an appropriate solution. The formation evaluation logging technique may require modification if non-aqueous drilling fluid is used.

7.3.3 Production Casing Hole Section

A salt saturated drilling fluid shall be used when drilling halite formation. The use of this drilling fluid maintains a reasonable borehole profile, which is more conducive to achieving quality wireline logging and cementing. Control of the viscosity, density and solids content is critical to maximize drilling ROP, and to maintain overall borehole stability.

If highly soluble salts such as KCl and magnesium chloride (MgCl₂) are present, sodium chloride saturated drilling fluids can induce further dissolution and therefore shall be avoided. Non-aqueous drilling fluids may be used in the production hole section of a storage well if potassium or magnesium chloride inhibition is insufficient. If highly soluble salt stringers are encountered, the non-aqueous drilling fluid system maintains borehole stability and profile. The formation wireline logging evaluation may require modification if non-aqueous drilling fluid is used.

7.3.4 Cavern Hole Section

For drilling any halite formation, the use of sodium chloride saturated drilling fluid shall be required. The use of this drilling fluid maintains a borehole profile that allows for higher quality wireline logging. Monitoring of the density and solids content is critical to maximize drilling ROP, and to maintain overall borehole stability. If the salt formation contains high potassium content, sodium chloride saturated drilling fluids can induce further dissolution of the highly soluble salts and should be avoided.

Non-aqueous drilling fluids may be required in the cavern interval of a salt storage well if the salt has a high potassium content. The non-aqueous drilling fluid system maintains borehole profile by minimizing or eliminating washouts in the salt. The formation wireline logging evaluation techniques may require modification if an non-aqueous drilling fluid is used.

7.3.5 Lost Circulation

Lost circulation is a decrease in the volume of drilling fluids returning to the surface. This can be due to drilling through relatively low pressure, highly porous, fractured, or vugular formations. The loss of circulation can be encountered almost anywhere in the borehole above the top of the salt. Most commonly in domal salt drilling, it is encountered at the top of the caprock, within the caprock, or at the caprock-salt interface. Precautions should be taken to maintain the drilling fluid weight as low as possible. If lost circulation does occur, steps to alleviate the problem should be initiated immediately. The use of nut shells and other interlocking fibrous additives have been found to help reestablish circulation. Setting a cement plug across the lost circulation zone is another method that has been successfully employed.

Operators should prepare a detailed lost circulation plan prior to drilling a well to ensure a timely and cost effective response. Lost circulation issues can result in loss of borehole stability, loss of pressure control, and in severe instances, loss of the well.

7.4 Drilling Guidelines

7.4.1 General

The following sections include general guidelines and/or practices that have proven successful throughout the industry when drilling liquid storage wells in salt.

7.4.2 Hydrogen Sulfide (H2S)

Due to geological conditions, H2S may be encountered during drilling. Rigs should be equipped and drilling personnel should have safety training to work in areas known to have H2S or have a history of sulfur mining. The operator should develop and implement a plan to monitor for and to mitigate the risks
posed by H2S during the drilling and completion operations.

7.4.3 Driven Conductor Casing
Prior to driving this pipe, an external drive shoe should be installed on the bottom of the first joint to assist the operation. The drive shoe helps ensure that the casing does not collapse during driving operations.

Care should be taken at the start of driving this pipe to be certain that it is being driven as vertical as possible, even to the point of starting over if it begins to deviate.

Typically, drive pipe is driven using a crane to hoist the pipe and the drive hammer. In some instances, this pipe is driven after the drilling rig has been rigged up.

The drive hammer shall be sized properly to assure that the pipe is driven to the desired depth and that the pipe is not fatigued during the hammering process.

7.4.4 Surface Casing Hole Section
Shallow formations are often unconsolidated, and therefore drilling can typically be accomplished quickly. High ROP could overload the solids handling equipment due to the large volume of cuttings produced. In order to avoid loading up the hole and overloading the solids handling equipment, the ROP should be limited to the capabilities of the solids control equipment.

A high viscous sweep should be performed regularly in order to clean the cuttings from the wellbore and to keep from loading up the hole with cuttings and causing loss of circulation.

7.4.5 Intermediate Casing Hole Section
The use of a shock-sub while drilling the caprock portion of the well can reduce axial impacts to the BHA and can help to protect the rig from excessive vibrations.

When drilling through cap rock typically found above domal salt structures, the dry drilling method may be used. In this method, drilling is continued without fluid returns to the surface. During dry drilling, high viscous sweeps should be performed regularly in order to clean the cuttings from around the BHA, reducing the potential for sticking the BHA.

7.4.6 Production Casing and Cavern Hole Sections
Common practice is to drill to final cavern total depth (TD) after setting the intermediate casing. This allows for the operator to more accurately define the salt section, thereby providing more optimal selection of the production casing seat and cavern total depth.

In order to assure the solution-mined cavern is developed in a symmetrical manner, a vertical-hole automated drilling system should be used in drilling the production casing and cavern hole sections. This also facilitates a good cementation of the production casing and decrease stresses on the hanging strings at the production casing shoe.

7.5 Logging
7.5.1 General
When specifying the logging program to the logging company, the types of drilling fluids planned to be in the wellbore during the logging operations should be communicated.

The overall length of the logging tools and the position of the first readings from each tool should be obtained from the logging company. These measurements should be used in determining the optimum depth to drill each section of hole. By drilling the section of hole to this optimum depth, the most complete amount of geological data can be obtained including the base of USDW, the top of caprock, and the salt-caprock interface.

To ensure sufficient clearance for all logging tools, the internal diameter of the tubulars, wellhead spools, and valves should be determined prior to running any logging tools in the well.

7.5.2 Open-Hole Logs
To properly evaluate the geological formations penetrated during the drilling operations, a suite of open-
hole logs should be run. The recommended formation evaluation logs are discussed in more detail in 5.3.2.3 and Annex A.

In addition to these formation evaluation logs, a gyroscopic log should be run for each hole section to determine the exact wellbore path and the bottom-hole location of the well bore in relation to the surface-hole position.

A caliper log in the open borehole should be run to determine the approximate volume of cement required to fill the annulus for each casing string cemented. During this caliper log, the tool should be pulled some distance inside of the previously set casing in order to verify the accuracy and calibration of the tool.

A static temperature log should also be run once the well has been drilled to TD to establish a pre-operating temperature profile of the entire wellbore.

### 7.5.3 Production Casing Logs

A casing inspection log which uses either magnetic flux leakage or ultra-sonic measurements to establish the production casing's wall thickness baseline for future comparison should be run. The magnetic flux leakage log can differentiate between internal and external metal-loss (corrosion), metal-gain (external hardware), and can also distinguish between general corrosion and isolated pitting.

A multi-finger caliper log should be run to establish a baseline internal diameter in order to identify possible casing wear, scale build-up, and ovality.

An acoustic or ultrasonic cement bond log on the production casing should be run, provided the tool response is adequate for the size of casing to be logged. Sufficient time after cementing shall be given before running this cement bond log.

### 7.6 Casing Handling and Running

On threaded and coupled casing strings, the bottom few joints of casing run into the well are usually thread-locked (permanently sealed together with an activated epoxy-like material) to avoid the possibility of unscrewing during subsequent drilling operations.

Refer to 8.3.8 for additional information on handling of threaded casing.

When the casing is welded, two joints may be welded on the ground prior to running into the well. Derrick opening height and width shall be taken into account when these two joints are lifted and positioned over the wellbore. Due to the weight and the length of the double jointed pipe, the lifting of these joints into running position should be done with a crane.

Refer to sections 6.4.5 and 6.4.6 for additional information on welded casing.

### 7.7 Cementing

#### 7.7.1 General

The cement program shall be designed to provide isolation of the storage zone from all sources of porosity and permeability and secure the casing in the borehole. All cemented casing strings shall be cemented to surface.

Cement quality and testing shall meet or exceed API 10A.

Laboratory testing should be conducted on all proposed cements and actual mix water. Non-salt saturated cements should include tests for 24, 48, and 72 hour compressive strengths at temperatures expected in the wellbore. Salt saturated cements should include tests for 24, 48, and 120 hour compressive strengths at temperatures expected.

Additives to control free water and fluid loss along with possible expanding agents should be considered.

An evaluation of an open-hole caliper log can determine excess cement volume.

The amount of time to wait after cementing and before any drilling activity can take place inside of the cemented casing is dependent on the development of compressive strength of the cement. Refer to subsequent sections on casing for more information.
7.7.2 Hardware

The proper casing hardware is essential in facilitating a successful casing and cement placement.

A float shoe should be used rather than a guide shoe as a float shoe contains a minimum of one internal back pressure valve. A down-jet float shoe should be used if there is a concern that getting the casing to bottom may be a problem.

A float collar should be run one casing joint length above the shoe and should contain a minimum of one internal back pressure valve.

For cementing down casing sizes greater than 13 3/8 in., the inner string placement method should be used (see 7.7.5.1), which requires a stab-in type float collar. A standard float collar can be used with casing sizes 13 3/8 in. or less and if the displacement placement method is used.

Casing centralization shall be used to achieve the placement of the cement around the casing. The goal is to place the casing as centered as possible in the wellbore to maximize the flow area for cement evenly around the casing.

The recommended minimum goal for standoff is 75% to 85%. Casing standoff should be modeled so that the centralizer number and placement can be determined.

There are two main types of centralizer design:

a) bow spring type, and

b) positive/rigid type.

A bow spring type centralizer is often run in a vertical well and in open wellbore sections where they help reduce casing drag on the wellbore during casing running operations. Bow spring centralizers are designed with restoring forces necessary to achieve maximum wellbore standoff to prevent fluid channeling due to casing eccentricity. The bow spring centralizer can be run through hole restrictions in the wellbore or through smaller casing strings that are cemented in the well, thereby centering the casing below the restriction. A positive/rigid centralizer is mainly used in deviated wells where it is not conducive to use bow spring type centralizers because their restoring force can be exceeded.

7.7.3 Primary Cement Slurry Design

The primary cementing is the original cementing operation performed after the casing has been run in the hole.

Primary cement slurries should be designed to be either neat, those without additives, or with additives for specific purposes (e.g. lost circulation, accelerated setting times, lightweight, water loss properties, gas block properties, rheological properties, expansion properties).

The cement slurry for a particular well can be designed with either one type of cement or with multiple types, pumped in stages, i.e. lead (first pumped) and tail cements (last pumped).

Slurry properties including rheology and compressive strength development should be tested for placement of the cement slurry and the resulting cement sheath.

A salt saturated cement slurry has 37.2% salt by weight of water. The salt should be dry blended with the cement. It is not recommended to mix the dry cement with brine to create the salt saturated slurry.

The compatibility of the make-up water with the various cement slurries should be tested.

An excess cement volume shall be determined following the evaluation of an open-hole caliper log of the wellbore.

7.7.4 Spacers and Flushes

Drilling mud can contaminate and weaken cement. Spacers and flushes should be used ahead of the cement slurry to displace a freshwater, saltwater or non-aqueous drilling fluid, leaving the casing and formation water-wet (free of oil).

Conditioning the annular area increases the chances of a good cement bond and decreases the
likelihood of cement remediation due to poor cement bond. In addition, spacers and flushes separate the drilling fluids from the cement slurry to prevent cement contamination with the drilling fluid.

Spacers are used to displace drilling and/or formation fluids from the wellbore and have enhanced rheological properties.

Flushes are used to thin and disperse drilling-fluid particles and do not have enhanced rheological properties.

Spacer performance depends on:

- rheological properties at wellbore temperatures;
- compatibility with the mud and cement;
- volumes needed for adequate separation between the mud and cement; and
- contact time, with regard to pump rates, and proper annular heights for drilling fluid removal.

### 7.7.5 Placement Methods

#### 7.7.5.1 Inner String Method

Due to the larger diameter casings used in cavern construction, cementing down the inside of casing greater than 13 3/8 in. often requires the entire volume of cement be pumped prior to the cement reaching bottom, which can limit the ability to make real-time changes to the cementing procedure. In these cases, the inner string method of cement placement should be used. Inner-string cementing allows cementing through drill pipe or tubing, using a stab-in type float collar.

The inner-string cementing method provides the following advantages.

- Large-diameter cementing plugs are not required.
- By pumping through the smaller inner string, cement contamination resulting from channeling inside the casing can be reduced.
- Cement is discharged outside the casing much faster after mixing, reducing the risk of a cement with a highly accelerated setting time prematurely setting up within the casing.
- Reduces the amount of cement that has to be drilled out of large-diameter casing.
- Less circulating time is required with inner-string cementing.

The inner string method does not allow for the casing to be reciprocated or rotated during the cementing job, techniques that have proven to facilitate circumferential cement placement and bonding.

A stab-in sub (sealing adapter) is made-up onto the bottom of the drill pipe and is used to stab into the built-in sealing sleeve of the float equipment for sealing the annular space between the drill pipe and casing. When using this method, a centralizer should be placed on the inner-string directly above the sealing adapter to help ensure that the adapter enters into the sealing sleeve properly.

A cementing/pack-off head with a pump-in sub should be used at the surface to seal the annular space between the drill pipe and the casing being cemented in place. The head also assists in preventing the collapse of the casing during the cement placement.

#### 7.7.5.2 Displacement Method

For cementing conventional sized casings (13 3/8 in. or less), a single stage displacement type cementing method can be used. In this method, cement is pumped directly down the ID of the casing.

The displacement cementing method provides the following advantages:

- reduction in rig time to prepare for the cement slurry placement;
- allows the manipulation of the casing during the placement of the cement slurry;
- allows for higher cement slurry pumping rates.
With a cementing head installed, the casing should be circulated clean before the cementing operation begins with at least one casing volume circulated. The first cement plug should be a wiper plug, which is pumped down ahead of the cement to wipe the inside of the casing clean. The flush or spacer is then pumped into the casing. The spacer is followed by the cement slurry, which should be followed by the second, shut-off plug.

When the bottom wiper plug reaches the float collar its rubber diaphragm is ruptured, allowing the cement slurry to flow through the plug, around the shoe, and up into the annulus. At this stage the spacer is providing a barrier to mixing of the cement and drilling fluid. When the solid, shut-off top plug reaches the float collar it lands on the bottom wiper plug and stops the displacement process. The pumping rate should be slowed down as the shut-off top plug approaches the float collar and the shut-off top plug should be gently bumped into the bottom wiper plug. The casing is often pressure tested at this point in the operation. The pressure is then bled off slowly to ensure that the float valves, in the float collar and/or float shoe, are holding.

7.7.6 Topping Off

A top-off cement is a cement slurry that is used to fill the annular volume behind the casing near the surface. If the primary cement dropped back down the hole, any voids should be topped off when cementing the large diameter cavern wells to add structural support and near surface corrosion resistance.

7.7.7 Surface Casing Cementing

Lightweight fresh water cement slurries can be used as a lead cement for filling the cased hole and open-hole sections with low fracture gradients, followed by a denser tail slurry. Heavier neat fresh water slurries, those without additives, can be used as the tail slurry across the base of the USDW.

7.7.8 Intermediate Casing Cementing

The primary function of the intermediate surface casing cementing is to secure and support the casing through usually unconsolidated overburden and into a cap rock or isolation zone to prevent undesirable migration of fluids from other formations through the annulus formed by the borehole and the outside of the casing. Lightweight fresh water cement slurries can be used as a lead cement for filling the cased hole and open-hole sections with low fracture gradients, followed by a denser tail slurry. Heavier neat fresh water slurries, those without additives, can be used as the tail slurry across the top of the cap rock or isolation barrier.

7.7.9 Production Casing Cementing

The primary function of the production casing cementing is to secure and support the casing through overlying layers and rock salt to above the cavern roof to prevent undesirable migration of fluids and/or gases from the cavern through the annulus formed by the borehole and the outside of the casing. Cementation of the production casing is critical particularly around the casing seat. A bond shall be achieved between the casing, cement and the surrounding salt to ensure a seal.

Lightweight salt saturated cement slurries can be used as a lead cement for filling the cased hole and open-hole sections with low fracture gradients, followed by a denser, low permeability salt saturated tail slurry.

A minimum of 95% of the 120 hour compressive strength is recommended at the casing shoe prior to testing or drilling out the shoe. The minimum wait on cement time before drilling out is dependent on compressive strength lab test results of the salt saturated slurries used.

7.7.10 Pump Rates

Pump rates should be designed to create turbulent flow and should be based on the fracture gradients of the open-hole formations, buoyant forces exerted on the casing, and if applicable on the cementing string.

7.7.11 Sampling

To allow for future testing of cement quality, dry and wet samples should be collected.
Dry samples should be caught while loading at the cement bulk plant, and while performing the cement mixing on the well location.

Wet samples should be caught intermittently during the beginning, middle, and end of the cementing job.

7.8 Completion

Prior to running the hanging strings, all of the drilling fluid in the wellbore shall be completely displaced with clean, fully saturated brine water.

Because of the weights of some hanging strings, the normal practice is to have a drilling rig run these two strings, but a workover rig with casing jacks is also acceptable.

8 Cavern Solution Mining

8.1 General

A solution-mined salt cavern for liquid hydrocarbon storage use is developed in a naturally occurring bedded or domal salt formation. Solution mining requires drilling a well, circulating fresh or low salinity (raw) water down the well and withdrawing the resultant brine from the well. The salt in the formation dissolves, enlarging the wellbore to form a cavern.

This section covers the creation of a cavern following the drilling and completion of the well and wellbore through the start of liquid hydrocarbon storage service. This includes:

— design of the cavern and development phases;
— equipment and instrumentation;
— monitoring cavern development;
— performing workovers during solution mining (if needed);
— other solution mining topics including:
  o conversions of existing caverns to liquid hydrocarbon storage service,
  o cavern enlargement.

8.2 Cavern Solution Mining Design

8.2.1 General

As cavern geometries (shape, depth, size) influence cavern operations and integrity, geometries should be determined prior to the start of solution mining by running a cavern modeling program proven to be reliable for the type of salt (bedded or domal). See 8.2.6 for a description of cavern models.

8.2.2 Cavern Structural Components

8.2.2.1 Casing Seat

The casing seat is the deepest position where the last cemented casing (production casing) is securely affixed (by cement) to the salt borehole. Often, the casing seat and the bottom of the casing are one and the same, but can be different if cement bond is poor or if the salt is washed out behind the casing. It is important that a good pressure seal is created by performing a sound, viable cement job on the production casing.

An integrity test may be conducted after drilling and well completion, before solution mining. The production casing cement shall be given sufficient time to reach full compressive strength before pressuring the annular space to the maximum allowable operating pressure (MAOP). The test, if run, should be a nitrogen brine interface test. Since the test is conducted when only a wellbore is present (no cavern), many more repair options are available if a problem is discovered. Some issues that may be identified include the casing seat not having integrity, a leak in the production casing, a hanging string leak, and wellhead issues.
8.2.2.2 Cavern Neck

The cavern neck is 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.

The neck should extend below the casing seat to the cavern roof, for a sufficient distance below the casing seat to prevent roof strains from affecting the integrity of the cemented casing(s). The length of the neck should be equivalent to at least one-half the diameter of the predicted, fully developed cavern and should be confirmed with geomechanical modeling where possible.

Additionally, having a long neck with a small volume per foot of depth provides the ability to resolve smaller changes in the depth of the nitrogen/brine interface during mechanical integrity testing.

For thin bedded salt caverns, an analysis should be made to determine if a confining salt bed above the proposed roof can be used for the production casing in order to provide a neck. This salt bed should have the strength and impermeability to contain the liquid hydrocarbon should the existing roof fail. The casing seat should be located to just below the confining bed. If a neck is not possible, the maximum diameter should be limited based on geomechanical analysis of the salt and overlying formations.

8.2.2.3 Chimney

The cavern chimney represents the initial development of the main portion of the cavern. It can be developed as a part of sump development or alone after sump development. The chimney should extend from cavern TD, or higher if the sump is developed first, to the proposed roof of the cavern. The chimney is developed using direct circulation. See 8.2.4 for descriptions of the flow circulation modes.

8.2.2.4 Roof

The roof of the cavern is the section of the cavern directly beneath the neck where the cavern begins to widen. It is critical to develop a cavern roof that provides structural strength to support the weight of the overburden above the cavern. The shape of the roof helps determine the amount of load it can handle and the associated stress levels.

The shape and depth of the roof should be designed to enhance structural integrity of the cavern. The roof should be arched or conical (such as tapered or domed) in shape and be at a depth which provides a neck below the casing seat. An arched or conical shaped roof has an ability to carry higher loads as compared to a more flat, horizontal roof. Wide flat roofs should be avoided as well as a roof at or near the casing seat.

The roof shall be developed with detailed planning, modeling and execution. After the roof is developed, blanket material shall be placed and monitored so as to protect the roof from uncontrolled solution mining. See 5.5.2 for further information.

For thin bedded salt caverns, a dome-shaped roof may not be possible. In this case, the maximum diameter should be limited based on geomechanical analysis of the salt and overlying formations.

8.2.2.5 Walls

The walls of the cavern are the vertical or near vertical oriented sides of the cavern beneath the roof and above the cavern floor.

8.2.2.6 Floor

The cavern floor is the section of the cavern beneath the walls. In domal salt, the floor is covered by insolubles produced during the solution mining process. The floor of a bedded salt cavern is typically littered with rubble from collapsed, non-soluble beds within the salt structure.

8.2.2.7 Sump

A sump is mined during the early phase of cavern development to allow for the settling of insolubles embedded in the salt structure and released during the solution mining process. The sump should be large enough to handle all the insolubles produced during the entire solution mining process. The sump can be incorporated into the chimney development to reduce the number of required workovers.
8.2.3 Blanket Material

The blanket material stays atop of the water/brine creating an interface. Typical blanket material choices include oils of various types, liquefied petroleum hydrocarbon, and liquid hydrocarbon. An inert gas (nitrogen for example) can be used, but in practice is difficult to manage.

There are several options when choosing a blanket material for the solution mining of a cavern. The primary requirements are that it should be insoluble in salt; be immiscible with water and brine, and its density or specific gravity shall be less than that of water; should not damage the well casing or the storage cavern; and should be compatible with the intended stored product or removed prior to product storage.

The blanketing material performs the following functions:
- It prevents the removal of the salt-cement seal around the permanent cemented casing strings. The maintenance of this seal is necessary to preserve the integrity of the storage well in the vicinity of the cased hole.
- It provides the means of limiting the upward growth of the cavern.
- It may be used to control the shape of the cavern.

The depth of the blanket material shall be carefully monitored so that the location and shape of the cavern roof meets the requirements of the cavern. At no time shall the cavern be solution-mined when the casing seat and neck are not protected by a blanket material.

The position of the blanket-water interface shall be periodically verified with a wireline log. The calculated volume (or surface pressure) of blanket material shall never be solely used to verify blanket protection.

NOTE If a gas or liquid hydrocarbon blanket material is used, the blanket expands and compresses and fluctuates in depth as the result of changing static and dynamic pressures and temperatures within the cavern and well system. This fluctuation varies depending upon the blanket volume in question.

8.2.4 Flow Circulation Modes

8.2.4.1 General

The two modes of circulating fluids through the cavern system are direct and reverse modes. Both modes require a single well to be equipped with concentric hanging strings. If two or more wells are used, single hanging strings can be set in the multiple wells for use in direct or reverse flow.

Since the sump and chimney of the cavern should be developed first, the combination of hanging string depths and mode of flow is used to obtain the desired cavern shape. Traditionally a cavern is initially developed through direct circulation followed by reverse circulation. Direct circulation should be used to prevent produced insolubles from plugging the longest hanging string and to create the proper size and shape of the lower portion of the cavern. As the mining progresses, the well should be switched to reverse mining so that the upper portion of the cavern and roof can be correctly shaped.

8.2.4.2 Direct Circulation Mode

With direct circulation, raw water is pumped down the longest hanging string (lowest set string) and exits the bottom of the string into the cavern. The raw water then circulates through the cavern by flowing along the walls where it dissolves salt, gains saturation and becomes brine. The brine is removed through the shortest hanging string and out the well. This mode of operation typically results in low saturation of the brine being produced.

As this mode of circulation places raw water towards the lower portions of the cavern, direct circulation tends to enlarge the lower portion of the cavern with the end result being a teardrop or pear-shaped cavern.

8.2.4.3 Reverse Circulation Mode

When a cavern is in reverse circulation mode, raw water is injected down the shortest hanging string. The raw water quickly rises towards the top of the cavern and the brine/blanket interface then towards the walls and continues its circulation path back down the walls of the cavern where it dissolves salt, gains
saturation and becomes brine. Completing its circulation in the cavern, the brine is removed from the cavern through the longest hanging string and out the well.

The increased salt surface area below the water injection point allows for the water to obtain a higher saturation than with direct circulation and results in a higher saturation for any given flow rate. Reverse circulation tends to mostly enlarge the cavern above the water injection point upward to the blanket/brine interface.

Since the roof of the cavern is preferentially mined with this method, extra care shall be taken with roof control so that the salt neck below the casing seat is left intact.

### 8.2.4.4 Complex Methods

The development of cavern shapes approximating cylinders, spheres, or other geometric shapes requires multiple adjustment of one or more of the controllable factors affecting cavern development during the course of the solution-mining program. Figure 5 provides a brief description and comparison of several such methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Illustrations</th>
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</thead>
<tbody>
<tr>
<td>Flooding String</td>
<td>1. Two concentric circulation strings. 2. Inner (bore or brine mixing) string stationary. Remaining circulated at near total cavern depth. 3. Outer (wash or water injection) string movable. Remaining circulated to blanket and water interface. 4. Outer string and blanket and water interface positioned in stages. A1 through F1 illustrate progression of cavern development.</td>
<td>A1 A2 B1 C1 D1 E1 F1</td>
</tr>
<tr>
<td>Stationary Pipe</td>
<td>1. Two concentric circulation rings. 2. Inner (bore or brine mixing) string maintains constant position at near total cavern depth. 3. Blanket and water interface levels moved in stages to provide shape control. 4. A1 through F1 illustrate progression of cavity development.</td>
<td>A2 A3 B2 C2 D2 E2 F2</td>
</tr>
<tr>
<td>Movable Rings</td>
<td>1. Two concentric circulation strings. 2. Blanket circulation strings and blanket and water interface remain constant. 3. Develops cavity in series of horizontal layers. Vertical boundaries are set by blanket level at top and saturated brine at bottom. 4. Provides high degree of control but pipe position is critical. High cost. 5. A1 through F1 illustrate progression of development.</td>
<td>A3 A4 B3 C3 D3 E3 F3</td>
</tr>
</tbody>
</table>

![Figure 5 – Solution-mining Methods](image)

### 8.2.5 Factors Affecting the Solution Mining Program

#### 8.2.5.1 Allowable Operating Pressures

Operating pressures in the developing cavern should not exceed the MAOP, refer to section 9.1.

#### 8.2.5.2 Borehole Deviation

During drilling operations, the vertical deviation of the uncased borehole should be minimized. Any deviation, especially in the uncased borehole, will affect the orientation of the wash and solution mining strings. This could result in asymmetric cavern development due to nonvertical discharge of water into the cavern. The degree of any significant borehole deviation should be determined before the solution mining program begins.

#### 8.2.5.3 Salt Anomalies

Cavern development can be significantly influenced by the presence and disposition of insoluble...
materials within the salt or by stratification of such materials within the salt as beds. Asymmetric cavern growth and internal collapse of unsupported insoluble masses due to dissolution of the supporting salt are potential problems. The presence of such impurities or beds should be considered prior to initiation of the solution-mining program.

8.2.6 Use of a Solution Mining Model

A solution mining model should be used for the design and during the development of, at least, the first cavern of a liquid hydrocarbon storage facility. The model, modified after comparison to actual results obtained on the first cavern, may then be used for development of additional storage caverns.

The solution mining model may be used to predict the geometries of cavern shape during the phases of cavern development. A model may also be used to determine if and when cavern workovers may be required to shift the setting depths of the hanging strings, creating the desired cavern shape.

Salt properties; raw water injection and brine withdrawal flow rates; the number of days of direct and reverse circulation phases; and hanging string and blanket placement and movements are some of the many input parameters required by a model to provide an accurate prediction of cavern and roof shape.

The final pre-mining model should be seen as a starting point in the development of the cavern to its desired geometries. The model should be updated at strategic points in the cavern development timeline. Updates to the model's parameters include actual salinities, flow rates, and cavern sizes as measured by sonar surveys.

8.3 Cavern Development Phases and Control

8.3.1 General

A cavern is developed in phases. Each phase includes a set number of days, flow rate, and solution mining circulation mode (direct or reverse) (see Figure 5).

There may be as many as three distinct phases required to develop a liquid hydrocarbon storage cavern. These phases are:

- sump only (direct circulation),
- sump and chimney (direct circulation mode),
- upper cavern and roof (reverse circulation mode).

NOTE  With proper modeling, it is possible to completely develop a storage cavern without a workover having been performed. The intermediate hanging string can be modeled in a single position for both direct and reverse circulation and the long hanging string can be adjusted by a casing cut. Sonar surveys can be run through casing to verify.

Once solution mining of the cavern has started, comparisons should be made of actual mining results to those predicted by the model. Analysis of the actual versus predicted results could lead to adjustments to the mining plan. Adjustments could include resetting the blanket depth, cutting the hanging string to prevent plugging with insolubles and/or a workover to adjust the setting depths of both hanging strings. These actions should be completed to bring the actual results back in line with the model.
8.3.2 Sump Only Development

Sump only development requires the long string to initially be set at or near total depth of the borehole. The shorter string would be set at a point above but fairly close to the depth of the long string. The blanket material can be set at any point between the short string and the final roof position. Direct circulation is used to mine the sump to a volume determined by the model. The sump volume should allow for all the estimated insolubles expected for the remaining development.

Sump only development is more apt to be used when mining in bedded salt with relatively thin beds or in multiple well domal salt caverns to connect the boreholes. During this initial phase of cavern development, the inner hanging string is susceptible to plugging since it is almost immediately in the insoluble pile. Operations should avoid outages during this period and should not backflow the cavern well as this would force insolubles up into the string and cause plugging. One design technique that can mitigate backflow is the placement of a check valve on the water piping near the well. After an unintended outage, such as a power failure, a portable high pressure positive displacement pump may be used to restart the well if site pumps fail to do so. Once water flow has been established with the portable pump, the site pumps can be re-started. If flow cannot be re-established, the longest hanging string should be cut or a workover performed to re-set the plugged string.

NOTE A sump only phase may require a workover to re-position the hanging strings for further cavern development.

8.3.3 Sump and Chimney Development

A sump and chimney development phase should be used when developing caverns in relatively thick bedded salt strata or domal salt. This method requires the long string to initially be set at or near total depth of the borehole with the shorter string set in position for all future development. Blanket material should be set at or near the desired roof depth.

As in the sump only development, the inner hanging string is susceptible to plugging since it is almost...
immediately in the insoluble pile. Operations should avoid outages during this period and should not backflow the cavern well as this would force insolubles up into the string and cause plugging.

Sump and chimney development should continue until:

- the sump size is sufficient to handle the insolubles produced by future development, and/or
- the chimney reaches the desired volume and shape of the lower portion of the cavern.

NOTE The long hanging string may require multiple cuts to prevent plugging with insolubles and to re-position the long string for upper cavern development.

8.3.4 Upper Cavern Development and Roof Control

The location of the roof can change during the mining of a cavern. This upward growth shall be controlled by planned use of raw water injection points, flow rates and blanket material positioning.

Frequent interface logs as well as periodic sonar surveys shall be performed to confirm desired shape and volume.

The upper cavern and roof development should be performed in reverse flow mode. Reverse flow along with blanket adjustment are used to form the upper portion of the cavern and roof into the desired shape.

8.3.5 Control of Cavern Development

8.3.5.1 Cavern Growth Prediction

The effective capacity of a storage cavern may be expressed as the sum of the following variables:

- volume of salt removed with the effluent brine;
- volume of salt in solution in the developing cavern;
- volume of insoluble material removed with the effluent brine.

8.3.5.1.1 Salt Dissolution

The volume of cavern developed through salt dissolution cannot be determined by direct measurement of any single variable, such as volume of fresh water injected or volume of effluent brine produced, because an indeterminate amount of injected water insolubles and salt remain in the cavern in the form of brine. The properties of aqueous salt solutions are well documented in available literature. A reasonably accurate determination of total dissolved salt can be calculated using data derived from field measurement and brine tables.

The following data are required to calculate salt dissolution to predict cavern growth:

- volume of injected water;
- specific gravity and temperature of effluent brine;
- density of the rock salt as determined from published tables or analysis of core samples obtained during drilling.

The frequency with which the necessary field data should be gathered and calculations completed depends upon the immediate volume objectives to be attained, the rate of fresh-water injection, the accuracy desired from the dissolution calculations, and the resources available to carry out these activities. Generally, fresh water injection rates should be recorded continuously. Measurement of brine specific gravity and temperature should be monitored every 2 hours. The salt volume dissolved should be computed each day using the average specific gravities and temperatures over 24 hours.

8.3.5.1.2 Insolubles

Insoluble impurities exist in virtually all rock salt masses, domal or bedded. The major impurity is usually anhydrite (CaSO₄). The concentration and disposition of impurities varies with the location and geological characteristics of the salt mass. Dissolution of the surrounding salt results in the precipitation of impurities onto the cavern floor. A certain percentage of these insolubles will normally be removed from the cavern in the effluent brine. Their volume may be measured after they have been deposited in settling pits or
tanks used for surface separation of insoluble material from the brine. This volume is usually negligible in comparison to planned cavern volume. The volume of the remaining insolubles should be considered with respect to their impact on planned cavern capacity, since the bulk volume of these insolubles may be 30% to 40% greater than their original volume. Estimates of the total percentage of insolubles in the salt mass should be determined from core samples taken during the drilling phase or from other reliable geological data.

8.3.5.2 Blanketing-material Control

8.3.5.2.1 General

The blanketing material and water interface should be carefully controlled and monitored to protect the production casing shoe during solution mining operations. The blanket-water interface position also establishes an upper limit on vertical cavern growth. That fact may be significant in achieving the desired cavern shape, depending on the solution mining technique employed and the complexity of cavern shape desired.

8.3.5.2.2 Positioning

The position of the blanket-water interface should be verified with an interface log or similar method. Depending on a calculated volume of blanketing material to provide dissolution protection to a specified depth can be risky, especially if target depth is in the uncased borehole or developing cavern.

8.3.5.2.3 Monitoring

During the course of solution-mining operations, the blanket-water interface level should be monitored periodically to ensure the desired level is being maintained. Upward movement of the blanket-water interface level is indicative of the following conditions.

— Leakage in the wellhead components or the collars of the blanket string.
— Enlargement of the uncased borehole and cavern above the blanket-water interface due to leakage of unsaturated water through defective joints or holes in the exterior suspended string.
— Dispersion of blanketing material due to horizontal cavern growth or turbulence at the blanketing material and water interface due to circulation.

8.3.5.2.4 Handling

All blanketing material should be handled to guard the safety of workers and to protect the environment. Storage facilities should be planned to accommodate the characteristics of the material and applicable codes and regulations pertaining to its storage, handling, and disposition.

8.3.5.3 String Placement

8.3.5.3.1 General

The placement of the wash and solution-mining strings determines the fresh-water injection and brine removal points within the developing cavern. The depths at which these strings are positioned relative to the surface and to each other are influenced by overall cavern development objectives and the complexity of the solution-mining program required to achieve those objectives. Cost and the particular phase of cavern development are also factors in this analysis.

8.3.5.3.2 Positioning

The position of the wash and solution-mining strings determine the following.

— The lower limit of cavern development, as the dissolution of salt below the deepest projection of the wash or solution-mining string continues only to a limited extent, regardless of the solution-mining technique employed.
— The lower limit of blanket-water interface level, as containment of the blanketing material and the maintenance of a stable blanketing material and water interface requires positioning of the blanket-water interface level at a point above the end of the most shallow of the wash or solution-mining strings. Because the minimum depth of blanketing material is governed by the need to
protect the cemented casing strings, the position of the shallow string essentially defines the range of the vertical interval to which the blanket-water interface level may be controlled. This constitutes a significant constraint on the use of the blanket-water interface level to limit upper cavern growth.

Multiple repositioning of the wash and solution-mining strings after initial placement can result in significant cost in equipment, manpower, and time. A cost-effective solution-mining program should seek to minimize the need for repetitive repositioning of these strings while achieving cavern development objectives.

8.3.5.3.3 Verification

The downhole position of the wash and solution-mining strings should be verified before the start or resumption of solution-mining activity. This may be accomplished by a summation of the measured lengths of each casing joint in the respective string prior to placement downhole. A collar locator or other suitable log may be used to verify the position after placement.

8.3.5.4 Source Water Injection Monitoring and Control

Salt dissolution and the resulting cavern growth are directly proportional to the rate and salinity of the source water injection. Accurate measurement of this variable enables salt dissolution calculations and allows prediction of cavern volumes. The injection rate and pressure should be controlled to provide uniformity in measurement and to prevent excessive pressure.

Water injection rates should be metered and recorded continuously throughout the solution-mining cycle. Temperature compensation should reflect all measurement relative to the base density of water at 60 °F (15.5 °C).

Rate data should be converted to volumetric data via continuous integration using appropriate instrumentation.

Instrumentation for flow control should be provided to permit adjustment and stabilization of flow rates in accordance with solution-mining program objectives.

Constraints on cavern operating pressures imposed by allowable operating gradients should be observed during the solution-mining phase of cavern development. Pressures within the storage cavern should be limited; the maximum pressure at the end of the deepest cemented casing string (the casing shoe) should not exceed the depth of this casing string multiplied by the allowable operating gradient. The corresponding pressure limit measured at the surface would be the calculated maximum pressure minus the incremental hydrostatic pressure imposed by the blanketing material from the surface to the casing shoe of the deepest cemented string. Instrumentation should be provided to monitor the pressure within the annular space occupied by the blanketing material. Abnormal pressures above calculated limits should trigger audible or visible alarms and isolate the cavern from the pressure source, preferably by shutting down the water injection pump. In general, abnormally high blanket pressure indicates flow restriction in the solution-mining string due to salt plugging or salt precipitating and adhering to the pipe wall. This phenomenon is caused by relatively rapid cooling of highly saline brine as it exits the storage cavern and is characteristic of the reverse-solution mining technique.

8.3.5.5 Control of Insolubles

The precipitation of insoluble material onto the cavern floor as a consequence of salt dissolution will reduce planned cavern capacity and inhibit lower cavern growth. In addition, it may result in flow restriction or plugging of the deep suspended tubing strings unless these insolubles are removed or otherwise controlled.

Insolubles control is achieved by the following:

a) removing the insoluble precipitates with the effluent brine;

b) allowing the insolubles to settle in a sump created below the maximum working depth of the storage cavern;
The selection of a primary method depends upon the estimated quantity of insoluble material, restrictions upon cavern geometry imposed by design or geological constraints, and any environmental restrictions associated with surface disposal of insoluble material.

A certain amount of insoluble material will normally be removed from the cavern in the effluent brine during the course of solution-mining operations. Insolubles can be removed on a larger scale by creating sufficient flow turbulence within the cavern so that some of the insoluble precipitates will ultimately be discharged from the cavern with the effluent brine. Problems with separation of insolubles from the brine at the surface and subsequent disposal of insoluble material may be significant and should be reviewed.

A cavern sump, created below the maximum operating depth of the storage cavern, should be used as the primary means of insolubles control, if practical. Sump capacity should be based on the total bulk volume (rather than original volume) of the insolubles projected to be generated and precipitated to the cavern floor. In bedded salt, any estimate of sump capacity should include a consideration of the insolubles content of the layered salt plus the additional volume of sedimentary strata, which may collapse as a result of dissolution of the supporting salt.

### 8.3.6 Monitoring Cavern Growth

Cavern development should be checked periodically by sonar caliper or other suitable methods to verify that the size, shape, and direction of growth of the storage cavern are in accordance with solution-mining program objectives.

The sonar caliper tool uses sound waves to determine cavern shape. A sound pulse from the transmitter is reflected from the cavern wall and is detected by a receiver in the tool. The travel time of the sound wave indicates the distance traveled, since the velocity of sound in a fluid of given density is known. The travel time should be adjusted for the estimated brine density at the time of the sonar survey. The transmitter/receiver unit can be rotated through 360° in incremental steps of 5° or less. At a given depth, a full rotation of the tool can provide a horizontal cross section of the cavern. By varying the setting depths of the tool incrementally over the total height of the cavern, a composite description of the cavern in terms of shape and direction of growth can be obtained.

Additional computation can yield estimates pertaining to incremental volume-per-unit depth and total volume. In addition to its rotational capability, the tool can be vertically oriented incrementally from 0° (horizontal) to approximately +90° (vertical). This permits mapping of the cavern roof to determine the presence of any irregularities that may affect the stability of the roof or may be potential entrapment sites for stored product during storage operations.

Cavern volume and shape may also be estimated from controlled displacement of the cavern with product; the product and brine interface location is subsequently determined for a specific volume of injected product. The location of the interface is then determined by an interface log or by computation using static well pressures and the density differentials between product and brine. Correlations between cavern depths may then be used to obtain approximate cavern shape. The feasibility of using this method during the solution-mining phase should be evaluated on an individual basis.

The frequency with which cavern growth is checked depends upon the method used and the complexity and objectives of the solution-mining program. Monitoring intervals should be adjusted to fit the requirements of the specific solution-mining program or regulations.

### 8.3.7 Emergency Shutdown (ESD) Equipment

During solution mining, ESD equipment should be installed on caverns developed using a blanket of flammable liquid hydrocarbon. All flowline connections to a wellhead that could be opened during operations shall have ESD valve(s) installed at or very near the wellhead isolation valve (wing valve). This valve or valves should be part of an ESD system that automatically shut in the cavern in the event of an emergency (see 9.4.2).

An instrument flange or a spool piece with instrument connections may be used between the wing valve and ESD valve. The wing valve can be opened slightly while the ESD valve remains closed to gather real-time pressure data when the cavern is not in use. The instrument flange or spool piece shall be rated for
the same pressure as the valves.

8.3.8 Hanging Strings

8.3.8.1 General

The injection of fresh water and removal of produced brine are accomplished through two hanging (non-cemented) strings of pipe. These strings are suspended concentrically from within the wellhead for single well caverns and the bottom of these strings is below the production casing. Multiple well caverns require a minimum of two hanging strings that are typically placed in separate wells.

Raw water and brine flow can either be in direct circulation mode (raw water down the long string and brine out the shorter string) or reverse circulation mode (raw water down the shorter string and brine out the long string). In multiple well caverns, one (or more) well(s) are used for raw water flow and one (or more) well(s) are used for brine flow. Typically the annular space of each well contains the blanket material.

The setting depths of each string are based on the desired shape and geometry of the cavern.

Hanging string oscillation can occur during solution mining. Care should be taken to detect and correct oscillation (see Error! Reference source not found.).

8.3.8.2 Size

The sizes of the hanging strings shall be based on project or operational requirements including:

- the ID of the production casing;
- the required solution mining rates;
- whether the cavern is used for storage during cavern enlargement periods;
- whether the hanging strings are replaced after solution mining, or are removed for liquid hydrocarbon storage service;
- how long the strings are in service;
- whether the hanging strings are compatible with a through pipe sonar survey;
- whether the hydraulics (both direct and reverse modes) are compatible with the pumping equipment.

Differences between the service and use of hanging strings and pipelines preclude the use of standard pipeline design models for size, wall thickness, and maximum velocity calculations. These differences include temporary versus permanent service life; vertical versus horizontal service; single point suspension versus fully supported, threaded versus welded connections; and size limitations due to wellbore diameter.

8.3.8.3 Body Strength

Once hanging string sizes are determined, care shall be taken to fully establish the pressure requirements in both direct and reverse circulation modes. Strings shall be checked for both collapse and burst resistance. By nature of being a hanging string, an axial load is present and therefore reduces the collapse resistance of the pipe.

API 5C3 shall be used for hanging string evaluation and design.

8.3.8.4 Connections

Once grade and wall thicknesses have been developed, string lengths for weight and required joint strength should be determined in order to choose a threaded connection type (e.g. 8 round, buttress or modified buttress). Buttress, modified buttress, and premium threaded connections can withstand a much higher axial load than can v-shaped tapered threads (8 round). These connections provide a larger safety margin when using large heavy weighted hanging strings.

Buoyancy of hanging strings caused by the presence of brine shall be used to calculate required joint
strength and axial load.

### 8.3.8.5 Torque

Connections with premium threads (often proprietary) shall be made-up to manufacturer's specifications. Connections with API threads should be made-up according to API 5C1. [8] Make-up for round threads typically uses a torque as the primary specification and the position of the pin end in the coupling as a secondary indication of a proper connection. Buttress and premium threaded connections typically use a prescribed position as the primary specification and an estimated torque to aid in the make-up.

### 8.3.8.6 Pipe Dope

Connections that have a metal to metal seal require a lubricant to prevent thread galling and promote installation. Other thread designs may have a natural helical leak path and require a lubricant/sealant. Threads should be cleaned and inspected prior to installation of any thread compound. API 5A3 [9] provides recommendations for compounds pertaining to API threads. Also all thread compounds should be used per manufacturer's recommendations.

### 8.3.8.7 Setting Depth

Each phase of mining may be modeled with a solution mining model that is appropriate for the type salt encountered (bedded or domal).

### 8.3.8.8 Quality of Sonar Surveys

Sonar vendors should be consulted during the hanging string design process for recommendations on tubing and hanging string combinations known to enhance sonar survey performance. It is advantageous to have the capability to sonar survey a cavern without first performing a lengthy workover to remove the hanging strings. Most modern sonar tools have the ability to "see through" steel tubing; tubing size, thickness, corrosion, and grade has an effect on the quality of sonar surveys. The result can be sporadic or even have the absence of return signals which leaves the sonar survey incomplete and requiring interpretation.

### 8.3.9 Fluid Handling

Flow control equipment should be sized to handle the required project flow rates, and MAOP of the solution mining process. The proper piping and valves should be installed that allows the operator to regulate flow and direction of flow to the well. A manifold or wellhead design should be included that allows for change of flow in the cavern from direct circulation to reverse circulation. This set-up also allows for backwashing of the hanging strings in case of salt build up.

**NOTE** Salt build-up and location is detected by reduced brine flow and increased brine pressure (build-up in piping beyond the wellhead) or reduced brine flow and no build-up in brine pressure (build-up downhole).

Injection rates shall be metered and recorded throughout the solution mining process. Temperature compensation should reflect all measurement relative to the base density (1.0 specific gravity) of water at 60 °F.

### 8.4 Instrumentation, Control, and Shut Down

#### 8.4.1 General

During solution mining processes, the cavern system components shall have instrumentation control and shutdown devices to safely shut-in the cavern system in an emergency or when anomalous conditions are detected.

#### 8.4.2 SCADA Systems

Detection devices should be connected to the control system that shut cavern ESD valves when necessary to isolate the cavern. Supervisory Control and Data Acquisition (SCADA) Systems are used to monitor and control the solution mining processes. These systems allow operators to monitor the real time status of the caverns and make control changes necessary to meet operations demands. They also alert operators to system upsets (alarms) or shutdowns that may require some action by the operator. The operator may be on site or at a remote facility.
8.4.3 Alarms
Audible and/or visual alarms should be incorporated into the control and shutdown systems. These can consist of devices such as strobes, horns or SCADA alarms.

8.4.4 Overpressure Protection (OPP) System
If the plant pumps have the capacity to increase the pressure of the cavern over MAOP, then over pressure protection (OPP) systems shall be installed to prevent over pressurizing the cavern in the event that the brine production side becomes plugged, e.g. hanging string salted up, brine valve closed.

Pressure sensors should be installed on the wellhead to monitor blanket, brine, and freshwater injection to detect abnormally high pressures. Settings should be set below the maximum operating pressure but above normal operating brine pressure.

Gauges may be placed on the brine string on the wellhead to monitor pressure change during static and fluid injection withdrawal and injection periods. Abnormal pressure conditions could indicate a leak of hydrocarbons into the fluid column.

8.4.5 Excessive Flow Rate
A brine flow meter and transmitter should be installed to detect rapid increases in brine outflow rates. This equipment should detect a complete or partial failure of the brine string, and be tied into the alarm and shutdown systems.

8.5 Cavern Monitoring
8.5.1 General
Monitoring of the cavern shall be conducted throughout cavern solution mining and storage operations.

8.5.2 Injection and Withdrawal Readings
The size and shape of cavern growth is directly proportional to the rate of fresh-water injected into the cavern.

Flow rates and key well pressures should be checked periodically during the day for early determination of any abnormal operating condition. At minimum, flow totals along with pressure readings should be recorded, analyzed and archived daily.

8.5.3 Cavern Geometries
8.5.3.1 General
As caverns are solution-mine, the shape changes and size increases. The change in shape and size shall be monitored to make adjustments (e.g. tubing depth, mining direction, blanket level) during the solution mining process. The resulting data should then be fed into the solution mining model to predict cavern growth. The actual data should be compared to the model prediction so adjustments can be made to the solution mining plan. This ongoing evaluation of well data and modeling data helps ensure that the final cavern meets the desired cavern geometries.

8.5.3.2 Sonar Surveys
To assess the development of a cavern, a periodic sonar survey should be run. Special attention should be paid to the sump, walls and roof to determine any preferential solution mining or anomalies in the cavern. These data should be used to plan workovers, tubing and/or blanket adjustments, and flow direction. Sonar survey data should be used to check the accuracy of the mining model. Sonar vendors should be contacted for information on the accuracy of their sonar tools run in various media.

8.5.3.3 Brine/Blanket Interface Logging
Wireline logs, along with other methods (e.g. pressure monitoring), shall be used throughout the solution mining process to monitor the depth of the blanket material. Special attention shall be paid to these data, as unplanned interface movement either up or down is indicative of cavern development problems.
8.5.3.4 Other Surveys and Logs

Whenever a wireline log is run, an effort should be made to verify hanging string depths and verify the bottom of the cavern. The log should be tied back to the casing seat so that all logs, both past and future, can be directly compared.

8.5.4 Water Chemistry

Depending on the source of water used for injection, it should be tested for salinity, specific gravity, sand/silt, oxygen content, bacterial activity and dissolved gases (such as oxygen, carbon dioxide, sulfur dioxide). Water sources include, but are not limited to:

- wells (both fresh and saline),
- canals,
- seawater,
- river water,
- recycled water.

8.5.5 Returned Brine Salinity and Chemistry

The operator shall measure the salinity of the water entering the cavern and the brine leaving the cavern. By measuring the salinity, the amount of salt removed versus water injected, can be used for calculation of volume and efficiency of the solution mining process.

Once the salinity of the brine that is produced has been recorded, the amount of salt that has been produced during a given mining interval can be directly calculated. This information can then be used to plan future mining operations on the cavern. The brine should be checked for minerals including the percentage NaCl, KCl, and MgCl₂. By calculating the amount and composition of salt that is being removed during a mining interval, the operator has the ability to evaluate the cavern development and problems during mining can be discovered and addressed. These problems include less soluble salt, which would cause the cavern to grow slower, and more soluble salt, which could cause growth of the cavern that is not planned. Even though the volume of the cavern should be continuously calculated from the saturation of the brine, periodic sonar surveys should be run to verify size and shape of the cavern.

8.5.6 Corrosion Monitoring

Solution mining procedures and facilities should include a corrosion monitoring program. When designing a corrosion control program the following should be taken into account:

- wellbore casing program;
- influence of foreign direct-current sources;
- ground resistivity;
- quality of cement jobs;
- corrosive nature of the soil and formation fluids;
- potential oxygen sources;
- microbiology of the injection water;
- oxygen levels of the injection water.

While the cavern is being solution mined, the injection water and brine produced should be periodically monitored for Sulfur Reducing Bacteria and Acid Producing Bacteria along with dissolved oxygen.

The monitoring of casing and hanging strings for corrosion in a solution mining and/or storage cavern can be a difficult task. Corrosion monitoring is particularly difficult with single well caverns because the intermediate hanging string is not accessible.
8.5.7 Other Considerations

8.5.7.1 Preferential Mining

Cavern development can be significantly influenced by the presence of insoluble materials within the salt. Asymmetric cavern growth and internal collapse of unsupported salt could occur. Other salts, such as KCl or MgCl₂, may be within the salt formation, causing a differing dissolution rate that causes preferential mining. In bedded salt formations, these higher soluble salts can undercut upper strata and cause strain or even collapse. In domal salt, preferential mining tends to be at an acute angle to vertical due to the mechanism that forms the salt dome. Cavern development shall be monitored for preferential mining by thorough and periodic analysis of brine samples and periodic sonar surveys.

8.5.7.2 Salt Falls

Salt falls, sometimes referred to as salt sloughing or spalling, occur primarily from flaws or heterogeneities in the salt structure, "skin" damage, or improper solution mining techniques. These salt falls can result in the loss of hanging string(s), but rarely affect cavern integrity.

Structural flaws can cause salt falls during solution mining, or storage. Types of structural flaws include:

- differential movement within the salt mass (salt spines);
- areas with weak bonding of the salt crystals, sometimes referred to as "popcorn" salt;
- the incursion of higher solubility salts that cause preferential mining.

Skin damage occurs during solution mining and storage operations. Several feet of salt adjacent to the cavern walls and roof are affected by the stresses caused by temperature fluctuations and salt "flexing" caused by liquid injection and withdrawal. Micro-fractures can develop allowing for weakening of the affected salt. Liquid intrusion into the fractures can cause a differential pressure that causes the salt to fail.

Poor solution mining techniques that may lead to salt falls include the following situations.

- Failure to control the blanket material. Control of the blanket is crucial in developing a properly shaped roof and neck. A poorly shaped roof and/or neck can cause strains that can result in a salt fall. Blanket control shall be maintained at all times to protect the cavern roof and neck.

- Mining too long with tubing strings in the same position. Water injection in a single position in excess of the solution mining model can over enlarge a section of the cavern and reduce structural integrity. Any deviations from the solution mining plan should be remodeled for effectiveness.

- Blanket positioned too close to the injection point. If the blanket and injection point are too close, rapid over enlargement can occur at the blanket/brine interface due to the high volume of low salinity water concentrated in the interface area.

- Failure to maintain hanging string integrity. A hanging string leak in reverse flow can cause preferential solution mining resulting in a small height and large diameter volume without proper structural support. Hanging string integrity shall be maintained by careful monitoring of flow, pressures and salinity of the brine. Any deviation from normal of the flow/pressure/salinity relationship should be immediately investigated.

8.5.7.3 Gassy Salt

Some salt masses have entrapped gasses such as methane, carbon dioxide, or nitrogen within their structure. This gas may become freed during the solution mining process and collect in the production casing. If enough is produced, the blanket interface can be pushed downward affecting the roof location and development.

8.6 Workovers during Solution Mining

Periodic well workovers may be performed during mining operations for well inspection and/or maintenance. Any time the hanging strings are removed from the cavern, the strings should be fully
inspected by a qualified inspection company. Joints that do not pass inspection should be repaired or replaced.

There are several reasons for a workover during the mining process. These include but are not limited to re-setting the hanging strings to comply with the solution mining model; plugged or salted-up hanging string; leak in either hanging string; the loss of blanket integrity; and a partial or total loss of a hanging string.

When performing a workover, additional work may also be performed, including:
   - a sonar survey if significant cavern enlargement has occurred since the last workover;
   - inspection and maintenance of the components of the wellhead if a significant cavern enlargement has occurred since the last workover;
   - a nitrogen/brine mechanical integrity test if the cause for the workover was a well or cavern integrity issue regardless of the timing of the last workover.

8.7 Workover to Configure for Liquid Hydrocarbon Storage Service

8.7.1 Conversion from Solution Mining to Product Storage

Converting the completed cavern to product storage involves the following steps.
   a) Displacing blanketing material from the cavern and depressurizing the cavern to permit removal of suspended strings.
   b) Removing the wash and solution-mining-strings and associated wellhead components.
   c) Final casing inspection, including sonar.
   d) Installing operational brine strings. Brine strings should be inspected and tested before they are placed in the well. The position of suspended strings can be verified by logging after placement.
   e) Installing the remaining wellhead components and associated wellhead isolation valves. The wellhead should be pressure tested after installation in accordance with applicable test procedures as defined by the manufacture or other authority having jurisdiction.
   f) Installing the surface piping and instrumentation on the well.
   g) Perform MIT

8.7.2 Conversion Workover

Once the cavern is fully developed, a full workover should be performed. This workover should include inspection of the production casing, installation of the liquid storage wellhead (if not already installed) and a mechanical integrity test. The workover should also include pulling and inspecting the existing hanging strings, running a sonar survey in the open cavern, and installation of the brine string.

8.7.3 Removal of the Solution Mining Hanging Strings

The hanging strings used for solution mining development should be removed and inspected. If one (or more) of the hanging strings are to be re-used, then a full body electromagnetic and ultrasonic inspection, along with a thread and coupling inspection shall be performed. Any joint or connection that fails the inspection shall be discarded. Strings that fail the full body inspection should be discarded or at minimum shall have the burst and collapse pressures derated based on wall thickness loss. Connections that do not pass inspection shall be replaced with new cut threads (pin end) and new coupling (box end).

8.7.4 Inspection of the Production Casing

An inspection of the production casing shall be performed during the workover to configure the cavern for liquid service. Wireline logs should be run that measure wall thickness, ovality, and internal/external anomalies. Refer to Annex B.

8.7.5 Performing a Full-Cavern Sonar Survey

A sonar survey shall be run to make a final verification of cavern geometries (shape, size, depths) and to
ensure that there are no spatial features that could limit or make storage in the cavern infeasible. Shape limitations can include wings behind the production casing, growth too close to existing caverns, or ledges that do not allow the brine string to go to the bottom of the cavern. Areas of non-uniformity should be sonar surveyed on a tighter pattern than the rest of the cavern to give the best estimate of the size and shape in these areas. The cavern roof and floor should be sonar surveyed using a fixed position(s) close to each and shot at angles using a sonar transducer that articulates from horizontal to vertical.

8.7.6 Installing the Liquid Hydrocarbon Storage Service Wellhead

Wellhead and valves used during solution mining should be replaced during the workover to configure the cavern for liquid service. Any reused components shall be removed, inspected, and tested prior to reuse.

The wellhead configuration should be modified to include ESD valves for all wellhead valves connected to site flow piping.

8.7.7 Installing Brine Strings

The brine string may be new pipe with complete documentation including Mill Test Reports (MTR). If a used string is contemplated then it should have a MTR and be full body electromagnetic and ultrasonic inspected and tested as is stated in 8.7.3. Strings of unknown quality (salvaged strings) shall not be used. Each connection of the brine string shall be pressure tested to ensure integrity.

8.7.8 Conducting a Mechanical Integrity Test (MIT)

An MIT shall be performed on a cavern before it is put into liquid service. This test is run to ensure that the well system has integrity. The test may be a nitrogen/brine interface test or an alternate means of mechanical integrity testing. An MIT should also be performed after any significant enlargement of a cavern. See Section 10 for a holistic approach to cavern integrity.

8.7.9 Brine Monitoring Devices

When operating a cavern by injecting hydrocarbon liquid, the brine return system should be monitored to detect hydrocarbons escaping into the brine string. There are a number of devices that may be installed after the initial workover, including:

— hydrocarbon detectors;
— flow measurement to detect a rapid, unexpected increase in brine flow;
— pressure transmitters.

8.8 Existing Cavern Conversions

8.8.1 General

Existing caverns developed for a purpose other than liquid storage, shall only be converted if they meet the same criteria as those purposely developed for liquid storage. A thorough technical review shall be performed on all data including, but not limited to:

— saltback distance;
— cavern neck length;
— size;
— shape;
— solution mining history;
— salt characteristics;
— salt core analysis;
— MIT history;
— condition of the production casing;
— threaded or welded casing;
— number and depth of strings cemented into salt;
— proximity to other caverns;
— proximity to the edge of salt;
— proximity to adjoining property;
— subsidence monitoring data;
— use of the other caverns in the field.

8.8.2 Geomechanical Analysis

8.8.2.1 General

A geomechanical analysis of the cavern should be considered prior to conversion operations. The analysis should review the cavern's relationship to adjoining caverns and to the edge of salt. Further analysis should include stress, strain, and dilation of the salt pillar between the cavern and other caverns in the field.

8.8.2.2 Cavern Shape

The shape of the cavern shall be verified with an open-hole sonar survey. Attention should be paid to the shape of the top and bottom of the caverns, areas of upward solution mining and areas of lateral dissolution toward the edge of the dome or other caverns. It should be determined whether irregular shapes are caused by a poor solution mining program or is a characteristic of the salt structure. It should also be determined if an irregular shape effectively reduces pillar thickness between caverns or to edge of salt. Refer to 5.5.3.

8.8.2.3 Flat Roof

Specific cavern operating conditions for which the roof diameter becomes too large shall be determined by geomechanical modeling. The modeling should be performed to determine the minimum allowable operating pressure that would prevent damage to the salt, spalling or even failure of the roof. If there is sufficient salt structure above the roof and sufficient salt neck, the roof should be re-shaped by additional solution mining. The distance from the casing seat to the roof should be adjusted to mitigate tensile stresses in cemented casings caused by salt creep or by failure of the roof. Tensile failure of the casing can result in a loss of structural integrity.

Bedded salt caverns tend to have flat roofs, especially in relatively thin beds. Overlying bed strength should be determined, so as to model the developmental limits of the cavern diameter. Cavern roofs in thick beds can be developed in the same fashion as salt dome caverns.

8.8.2.4 Salt Neck

For domal caverns, if a salt neck is present in the converted cavern it should extend for a sufficient distance below the casing seat to prevent roof strains from affecting the integrity of the cemented casings. It may be possible to develop a sufficient neck by relocating the casing seat to a higher level. Care should be taken that the remaining salt above the new casing seat is sufficient for the relocation. If a salt neck is not present, an engineering analysis should be considered prior to conversion.

For bedded salt caverns, a dome-shaped roof and neck may not be possible. In this case, analysis should be performed on the strength of the overlying beds versus diameter of the roof. Further analysis should be given to determine a confining salt bed above the existing roof. This salt bed should have the strength and impermeability to contain the product should the existing roof fail. The casing seat should be relocated to just below the confining bed, if analysis of the existing roof shows the possibility of failure. Caverns that do not meet these criteria shall not be used for liquid storage.

8.8.2.5 Adjacent Caverns and Edge of Salt

The proximity of a cavern being considered for conversion to adjacent caverns and the edge of salt should be evaluated. This evaluation should include a geomechanical study of the cavern operating conditions in relationship to each other, the behavior of the salt pillar between the caverns based on these...
operating conditions, and the salt at the edge of the salt mass, as the salt characteristics near the edge of salt may be different than from the rest of the salt. Sonar surveys should be reviewed carefully to see if there are any planes of weakness that could lead to cavern failure toward the edge of the salt. In addition, caverns that could be considered close to the edge of salt should have the casing seat location precisely determined. This includes running a gyro log on the wellbore and tying the sonar surveys exactly to this log. The borehole location should be shown on a salt contour map and the thickness of salt expressly evaluated for safety.

### 8.9 Cavern Enlargement

Caverns can be placed in-service and later enlarged over time to their maximum size. This type of enlargement may occur in the lower interval of the cavern. After a cavern has been placed into service, cavern enlargement may be used to regain volume lost to creep or to attain the maximum cavern volume.

Prior to commencing cavern enlargement, the following items should be modeled: the resulting cavern shape; spacing to other caverns, property boundaries, and edge of salt; and review of geomechanical properties.

During cavern enlargement, the liquid hydrocarbon-water interface should be closely monitored. The volumes of raw water injected and brine displaced should be compared to a cavern volume table to predict the liquid-brine interface level. Regular interface checks are recommended to verify the liquid-water interface and the accumulation of insoluble material. If the liquid hydrocarbon-water interface alters the shape of the cavern roof or has caused solution mining near the casing shoe, a mechanical integrity test shall be performed prior to placing the cavern back into liquid hydrocarbon service.

After any significant cavern enlargement, the volume of the enlarged section should be determined by a sonar survey.

### 9 Liquid Hydrocarbon Storage Operations

#### 9.1 Facilities and Equipment

##### 9.1.1 Brine Facilities Equipment

#### 9.1.1.1 General

Brine is used to displace the stored liquid hydrocarbons on a one to one basis. Therefore for the successful operation of the cavern storage system the proper handling of the brine is essential.

##### 9.1.1.2 Salinity

The storage field operator should be aware of the salinity of the brine being used in storage operations. The operator will want to establish procedures to monitor salinity based on the specific well configuration and operating conditions at the storage site. Brine can be either supersaturated or under saturated. Supersaturation can occur because of evaporation from the brine storage pond during extended periods of hot, dry weather or when a sudden temperature drop occurs reducing the solubility of salt in water. Supersaturation can result in operating problems usually manifested by precipitation and growth of salt crystals in pump cases, valve bodies, well tubing, etc., causing increased wear and eventual blockage.

Consideration should be given to installation of fresh water flushing systems to facilitate the dilution of salt crystals in critical equipment. The operator should also provide fresh water make-up to stored brine during hot, dry weather to maintain salinity at a point slightly less than saturated.

Undersaturation can occur naturally due to dilution by rain water or by an increase in temperature thereby increasing the solubility of salt in water, or intentional dilution with fresh water. Under saturated brine has the ability to dissolve salt, which will result in additional cavern growth. This effect should be considered in the operation of mature storage fields or in individual wells where further growth is not desired.

Undersaturation also results in a fluid which is less dense than saturated brine and may effect cavern hydraulics.

##### 9.1.1.3 Brine Sources

Brine needed for the normal operation of storage fields can be obtained from any combination of the
following sources:
- Brine production wells
- Brine storage ponds
- Purchase from other brine producers
- Local sharing agreements in multi-company storage areas

9.1.1.4 Brine Pond Storage

Normally brine is stored above ground in open ponds awaiting use for displacement of product from wells. To conserve brine and to prevent environmental pollution of land, surface water, and ground water, the pond should be equipped with an impermeable lining. In selecting a lining material, consideration should be given to compatibility with brine, hydrocarbon resistance, and ultraviolet deterioration. In some instances a compacted clay lining may be acceptable. Regulations shall be reviewed before lining a pond or making repairs to an existing lining.

Consideration should be given to installing a brine leak detection system. Acceptable systems include monitoring wells, french drains, double pit lining, or combinations of the preceding. Periodic visual inspection of the liner at various brine pond levels should be conducted. Regulations may dictate the need for and method of leak detection.

Small quantities of liquid hydrocarbon may be released when brine from a product well is returned to a pond.

Consideration should be given to the installation of a brine/product separation system or a liquid hydrocarbon detection system which could be used to provide an alarm or to shut down equipment.

The amount of brine storage to be provided relative to the total product storage is dependent on various factors such as the total active storage capacities, diversity of demand for individual products stored, the availability of replacement brine (i.e., brine sharing arrangement at multi-company storage areas), and brine disposal capacity.

Erosion of external dike walls should be controlled or prevented. Acceptable methods include reducing the slope of the dike walls, planting vegetation suitable to the climate, installing rip rap or environmentally safe stabilized topping, and providing periodic maintenance of the dikes.

Wave action in brine storage ponds can cause underliner dike damage or spillage of brine. Maximum fill levels should be established which allow an adequate freeboard to prevent spillage. In cases of severe wave action, consideration should be given to the installation of mechanical wave control. Regulations should be consulted for specific requirements.

Brine ponds are exposed to climatic conditions. These include evaporation, dilution, precipitation, and collection of blowing dirt and sand. In the installation of a brine pond, the operator should consider and allow for contraction and expansion of the liner materials under climate extremes with low brine inventories in the pond. Most pond liners are black and collect significant amounts of solar energy resulting in higher brine temperature at the bottom of the pond. Most brine ponds have pump suction at the bottom of the pond. The brine delivered to the well may be supersaturated and at a higher temperature than the brine in the well. The potential effects on product flashing or hydraulic pressure gradient of operating wells should be considered. Piping should be designed to allow fresh water connection to the brine pumps for flushing the suction piping to clear salt from the pump casing and piping.

9.1.1.5 Disposal

Methods of brine disposal should be carefully considered. Where allowed by regulations, excess brine may be disposed of in permeable sand formations or oil production zones.

Operators near coastal areas may consider pipelining brine a suitable and permitted distance offshore. Alternatives to brine disposal include delivery to chemical plants as feedstock or brine sharing arrangements at multi-company storage areas.
Operators of brine disposal wells should maintain pertinent disposal records as required by regulatory bodies. These records may be analyzed by the operator to determine the condition of the well.

9.1.1.6 Pumping

Pumping brine at a storage facility is necessary to transfer brine to a disposal well, other ponds, or a storage well for product displacement. Brine movement can be accomplished with the same types of equipment readily available for other products, but consideration should be given to brine’s corrosive and erosive properties. When specifying the pump case, impeller shaft, bowl, bushing, packing sleeve, etc., the operator should consider material selection.

It is recommended that fresh water be provided for seal flush and for rinsing and dissolving salt deposits. Design and safety shutdown considerations are similar to product pumps.

Even small brine leaks create corrosive conditions on external cases and piping, which is not only unsightly, but also detrimental to system integrity. Surface preparation and the careful selection of external coating systems are important. Prompt attention to leak repair, cleanup, and spot coating repair is recommended.

9.1.1.7 Measurement

Measurement of brine can be accomplished by using the same types of equipment used for product measurement; however, the problem of salt precipitation and crystal growth necessitates more frequent maintenance and cleaning. Because of the stable properties of brine, properly designed and maintained equipment will provide accurate measurement data. Brine streams which should be considered for measurement include the following:

- Custody transfer
- Disposal
- Storage wells where product measurement is difficult or impractical
- Overfill prevention/detection

Regulations may dictate instances where brine should be measured.

9.1.1.8 Control

Brine-pressure regulating and relieving equipment need to be installed and maintained to provide a reliable source of brine at the proper pressure to prevent overpressure of piping and cavern wells. Control valves or stand pipes on brine return-lines to the ponds are common in the industry. Consideration should be given to installation of emergency shutdown equipment to prevent equipment damage or brine releases.

9.1.1.9 Product/Brine Separation Systems

Some product/brine separation systems include separator vessels or stand pipes, with the hydrocarbons piped to vents or flares. Dedicated product/brine separation caverns can also be piped into the brine return system.

9.1.2 Fresh Water Facilities Equipment

9.1.2.1 General

Fresh water facilities are essential to the construction of salt storage caverns and are typically used for various operations.

Examples of applications for the use of fresh water include:

a. Fire protection.

b. Flushing and desalting of wellheads, tubing strings, pumps, valves, etc.

c. Replacement brine production.

d. Stored brine dilution.
e. Bearing cooling, seal flush, etc.
f. Solution mining of existing or new storage caverns.

Consideration should be given to the quality of water as some contaminants can be detrimental to equipment and piping. In climates where freezing is likely, precautions such as heat tracing, extra depth pipe burial, heated pump houses, etc. are recommended. Sources of fresh water include wells, canals, rivers, and local utilities. In many areas the removal of water from waterways and under-ground formations is regulated by authorities and may require a permit.

9.1.2.2 Pumping

Pumping of fresh water can be accomplished using the same types of equipment readily available for other products, but consideration should be given to the corrosive and erosive properties of fresh water when specifying case and trim materials. Design and safety shutdown considerations are similar to product pumps. Due to the high pressures associated with washing caverns, particular attention shall be paid to ensuring protection against over-pressurization of the caverns in the event of inadvertent brine discharge shut-in. Surface preparation and the careful selection of external coating systems are important. Prompt attention to leak repair, cleanup, and spot coating-repair is recommended.

9.1.2.3 Measurement

Measurement of fresh water can be accomplished using readily available positive displacement, orifice, or turbine meters. Measurement may be needed to satisfy permit requirements or to provide normally required operating data.

9.2 Minimum and Maximum Operating Limits

Using the area of the tubing and/or annulus a maximum flow rate for each string can be established. In addition, the maximum flow rate may be established on other criteria based on measured vibration and erosion testing.

Maximum storage operating pressures shall be established by the operator. The operator shall then convert the maximum and minimum pressure at the casing seat to a maximum and minimum product wellhead pressure. The brine and the stored product(s) density’s directly impact casing shoe pressures and potential ranges in these shall be taken into account when calculating allowable pressures, particularly when caverns may have potential product mixes. Sufficient pressure should be established to prevent product vaporization. Due to friction pressure losses in the inlet/outlet strings during flowing conditions, the operator should evaluate pressures during flowing as well as static conditions to verify that maximum allowable casing seat pressures are not exceeded.

The brine string should be operated to maintain a positive pressure. An alarm should be in place to alert the operator when the pressure nears 0 psi. If the pressure does drop to zero, product withdrawals should be slowed or stopped and measures taken to return to a positive pressure.

Maximum product inventory level in the cavern shall be established by the operator to prevent overfill and subsequent hydrocarbon product from entering the brine string. Inventory management tools incorporating flow meters and/or other instrumentation are critical in maintaining proper level control within the cavern(s).

9.2.1 Hanging String Oscillation

At times during liquid storage operations, the hanging string can begin to oscillate and can reach a resonant frequency. Operational procedures or installation of wellhead accelerometer(s) should be used to detect and correct this oscillation. Typically a change of flow rate, either up or down, corrects the problem. If the oscillation is allowed to reach resonance, correction may not be possible without completely stopping flow.

Uncontrolled oscillation can cause hanging string failure.

9.3 Backwash Operations

Brine strings may occasionally get salt build-up, potentially restricting brine flow and leading to high
operating pressures and/or blockage. Operators should monitor flowing pressures/flowrates and evaluate trends to determine need for back-flushing the brine string with fresh water to dissolve the salt build-up.

To backwash, fresh water is pumped into the brine string from the surface to a predetermined depth. Displacing the brine string with fresh water will cause the surface pressure on the brine string to increase due to the lighter water in the column. During this process it may be necessary to stop product injections into the cavern. The fresh water should sit in the brine string for a period of time long enough to dissolve the salt build-up. The fresh water is then bled back and displaced with brine from the cavern. The brine string pressure will be elevated so care should be taken when releasing the fresh water to keep flow rates within established parameters.

Another acceptable method of backwashing is to install a dilution string inside the brine string. When product is being received into the cavern, fresh water can be pumped down the dilution string to wash away salt buildup on the inside of the brine string and also remove blockages.

9.4 Equipment

9.4.1 Product Storage Service Wellhead

A wellhead designed specifically for liquid hydrocarbon storage service shall be installed during the conversion workover and prior to storage operations (see 8.7). The wellhead components that were exposed to raw water and brine flow during solution mining should be inspected or replaced prior to liquid hydrocarbon storage service, particularly valves and other well control equipment.

9.4.2 ESD Equipment

Each outlet shall have an Emergency Shutdown (ESD) Valve (fail-close) installed adjacent to the manual valves (wing valves). These valves should be part of an ESD system that automatically shut in the cavern in the event of an emergency. Consideration should be made to determine appropriate closing times for automated shutdown valves to prevent/minimize potential water hammer damaging effects on the wellhead/piping system.

An instrument flange or short spool may be used between the manual wing valve and ESD valve to gather real-time pressure data when the cavern is not in use. The flange shall be rated for the same pressure as the valves (see 6.5.11 and 8.3.7).

9.4.3 Flow Measurement Equipment

Each cavern should be equipped to measure product flow into and out of the cavern. Flow measurement is a critical tool in facility inventory control and monitoring, and is most often the primary measurement used to calculate cavern product levels during operations. These devices can be used to determine excess flow into/out of the cavern, and can also be used as a check on the flow metering at metering facilities. If brine flow monitoring equipment is installed, it should be incorporated into the safety system as a method to detect cavern overfill.

9.5 Instrumentation, Control, and Shutdown

9.5.1 General

Cavern system components shall have control and shutdown devices installed and designed to safely shut-in the cavern system in an emergency or when monitored parameters, such as pressure, flow, or product level exceed the maximum allowable values.

9.5.2 SCADA Systems

Supervisory Control and Data Acquisition (SCADA) systems are used to monitor and control liquid injection and withdrawal. These systems allow operators to monitor the real time status of the caverns and make control changes necessary to meet operations demands. They also alert operators to system upsets (alarms) or shutdowns that may require some action by the operator.

9.5.3 Alarms

Audible or visual alarms should be incorporated into the control systems to notify operations of abnormal conditions. These may consist of devices such as strobes, horns, or SCADA alarms.
9.5.4 ESD System
Each cavern shall have an ESD system installed to isolate the cavern and wellhead from any attached piping in an emergency. This system should be integrated into the overall facility SCADA and Shutdown System.

9.5.5 Overpressure Protection (OPP) System

9.5.5.1 General
An OPP system is designed to prevent overpressure of the cavern, production casing shoe, wellhead, or wellhead piping. The system automatically shuts in the cavern or isolates piping to block the source of the overpressure. Even when product/brine is not flowing, if the cavern is left shut-in, creep closure of the cavern will cause the pressure in the cavern to increase. Therefore the pressure in the cavern should be monitored at all times to ensure that the production casing shoe maximum pressure is not exceeded.

9.5.5.2 Pressure Monitoring Points
The product annulus should be monitored for pressure. A tap between the wing valve and the ESD valve should be considered. Tapping the wellhead inside of the wing valve shall not be allowed, as it is a potential source of uncontrolled liquid loss from the cavern if the isolation valve on the tap is damaged.

The wellhead piping pressure should be monitored to ensure the pipe pressure does not exceed the piping MAOP and the cavern is not pressured beyond the casing shoe maximum allowable pressure.

Low product pressure, high product pressure, high brine pressure, and the convergence of product and brine pressures can be used for alarming and/or shutdown.

The cemented annulus between the production casing and the next cemented casing should be monitored for pressure. Pressure increases could indicate a leak in the production casing or a micro-annulus leak through the cement from the cavern. Further investigation and testing would be necessary to determine cause of the pressure change rate.

NOTE Some caverns may not have an additional cemented casing annulus to monitor.

9.5.6 Overfill Protection (OFP) System

9.5.6.1 General
An OFP system is designed to prevent overfilling of the cavern with hydrocarbon product. The system automatically shuts-in the cavern to block the flow of hydrocarbon product into the brine system. If hydrocarbon product enters the brine string, a potential increase in volume of the product may occur, possibly causing an increase in pressure and excessive or elevated velocities within the brine string/piping.

9.5.6.2 Weep Holes
Weep holes are small cutouts near the bottom of the hanging strings. Weep holes allow a small amount of product to flow into the brine being displaced from the well prior to the product/brine interface reaching the bottom of the brine string. Pressure transmitters, excess flow meters, product-in-brine detectors, hydrocarbon detectors, and/or product/brine separation systems can detect this product in the brine and can provide early indications of the interface approaching the bottom of the brine string.

9.5.7 Fire and Hydrocarbon Detection
The appropriateness of fire and hydrocarbon detection should be evaluated for wellheads in hydrocarbon service. These systems are designed to detect fire, heat, or hydrocarbons.

Instrumentation for fire and hydrocarbon detection includes thermal melt-outs, thermocouples, hydrocarbon detectors, flame detectors, and others. The type of device or devices used depend on the location, layout of the wellhead, and engineering design requirements among other factors. Fire and hydrocarbon detection devices should be failsafe in that they should activate the ESD system upon device failure or loss of energy source (e.g. power, air pressure, gas pressure).

Flame detectors can be used to safely shut-in a cavern if a flame is detected on or near the wellhead and
associated piping. The type of flame detector used should be selected within the anticipated operating environment to maximize reliability while minimizing false alarms.

Thermal melt-out devices may also be used to activate the ESD system. This device fails if heated above a certain temperature by flame and results in cavern shut-in. These types of devices are a good choice for outdoor facilities as they are not affected by factors such as wind, lightning, or nearby welding.

9.6 Inspection and Testing

9.6.1 General

Wellhead gauges, transmitters, and safety devices should be tested and calibrated at least annually or as required by regulations to ensure they are properly calibrated and function as intended. Any malfunctioning equipment shall be repaired or replaced. If the devices cannot be calibrated to within manufacturer's specifications they shall be replaced.

9.6.2 Integrity Monitoring Program

See Section 10 for recommended practices regarding integrity monitoring programs.

9.6.3 SCADA System Checks

All safety related components of the SCADA system should be tested periodically to ensure critical operational data are accurate, alarms are properly calibrated and functional, and safety related equipment is functioning properly.

9.6.4 ESD System Testing

ESD systems shall be periodically tested to ensure they perform as intended in the event of an emergency. All components of the system should be functionally tested and calibration checked as appropriate (i.e. switches, valves, transmitters, electronic devices, and other end devices). Valves should be stroked fully open and fully closed.

NOTE It is recommended that operators conduct ESD System testing on a semi-annual basis.

9.7 Workovers

9.7.1 General

Well workovers may be necessary during liquid hydrocarbon storage service. Reasons include:

— partial or total loss of brine string;
— well or cavern integrity issue;
— maintenance of wellhead components; and
— regulatory requirements;

9.7.2 Workover Methods

9.7.2.1 General

Liquid cavern well workovers are conducted on both pressurized and depressurized systems.

9.7.2.2 Workover Planning

As the cavern is out of service during the workover, consideration should be given to inspecting and testing the downhole tubulars, the wellhead, valves, and associated equipment to verify the functional integrity of the cavern system. All gaskets, studs, nuts, etc. removed during the workover should be replaced. See Section 10 for guidance on available integrity monitoring methods.

Materials and service vendors should be selected carefully. Materials should meet or exceed industry codes and standards. The service vendors should have appropriately sized equipment that has been tested and verified to be in good condition, and be able to meet delivery and other timing schedules without sacrificing safety or quality.
9.7.2.3 Workover Safety Considerations

For a workover on a de-pressurized cavern, the well should be empty of hydrocarbon and full of brine. Prior to pulling the first brine string, brine should be circulated down the brine string and returned through the annulus, if possible, to assure the well is full of brine.

If it is suspected that hydrocarbons may be trapped in a washout above the last cemented string or other areas of the cavern, additional care should be taken. Perforation and milling of casing to expose the washout may be considered if well construction is conducive to this type of repair.

The operator should consider keeping a chronological record of the workover. The following list contains some suggested items to be included in the documentation:

a) The date the well was de-pressured
b) The date and times the well was vented
c) The date, time and amount of brine added
d) A written log of all work performed on a well during the workover
e) Results of tests and inspections
f) Findings, recommendations and immediate actions required, if any
g) Next inspection interval based on results of tests and inspections

Fire extinguishers should be available at the well site throughout the workover. Ensure that all installed fire hydrant monitors are operating properly prior to initiating any work.

A properly rated blowout preventer and/or annular blowout preventer capable of closing in the well at full expected hydrocarbon pressure should be installed when practical. It is a good safety practice to have tubing crossovers made with shut-in valves to install in each box connection while pulling the tubing.

If the wellbore is open to the cavern interval without well control equipment installed, additional safety considerations should be taken. It may be necessary to install an isolation packer or plug to remove product valves or the product spool.

9.7.2.4 The Workover

The well should be able to be closed in at any stage of the workover in the event product migrates to the surface from a roof or other area of trapped product. This process can be accomplished by the use of an annular or ram type blowout preventer, tubing shut-in valves, packers, or other methods. Ensure that pressure below the blowout preventer does not build up enough to push the tubing out of the well. If high pressures are encountered, vent off product below the blowout preventer if possible, or have a method of holding the tubing down.

Qualified personnel should inspect the wellhead spools, valves, flange faces/ring grooves, and hanger areas for signs of external or internal corrosion or other damage.

All wellhead valves should be inspected, tested and repaired or replaced as necessary.

All small pipe fittings, nipples, relief valves on the well head, ESD's, and wing valves should be inspected and repaired or replaced at each workover.

The brine string(s) should be inspected by a qualified inspector prior to installation or re-installation in the well. During tubing string reinstallation, consideration should be given to torque/turn monitoring, special thread sealants, or coupling pressure tests (internal or external).

The casing braden head and hanging-seal assemblies should be tested to ensure zero leakage.

A Mechanical Integrity Test (MIT) of the cavern system may be completed at the conclusion of the workover.

9.7.2.5 Additional Tests and Safety Devices

There are a number of logging tools available for downhole corrosion monitoring or for detecting potential
corrosion; see Section 10.1, Table 1 for additional details. These tools may be used to locate potential problem areas in wells or to verify that no corrosion exists.

Sonar calipers may be run during workovers to show the physical dimensions and volumes of the storage cavern. Such logs can be used to locate roof and sidewall irregularities or traps.

9.8 Site Security and Safety

9.8.1 General

Safety programs and procedures should be developed to mitigate safety hazards and risks. Safety programs should include facility safety, staff safety, contractor safety, and public safety.

The facility emergency procedures, as described above, should include actions to take to ensure public safety and protect the environment and should be implemented in the event of an emergency that could pose a risk to the public or environment.

The operator should evaluate the safety and emergency response benefit of closed circuit television (CCTV), access control, man-down systems, barriers, intrusion detection and perimeter control.

9.8.2 Mutual Aid Organizations

Many companies have chosen to form organizations with the community in which their underground storage facilities reside. Mutual aid organization operation allows emergency planning on a multi-company and community scale, much like the individual emergency plan at the plant site. Additionally, the community residents, business leaders, school officials, city officers, and the fire and police/sheriff personnel become informed and trained as to the emergency possibilities, evasive measures, and communication system.

9.8.3 Access Control

Access control can include automatic (lockable) gate, key pads, call buttons, badge readers, and cameras. These devices allow the remote monitoring and control of access points throughout the facility.

Perimeter control is normally provided by fencing, vehicle gates, and pedestrian gates.

Crash gates and strengthened fences can be utilized to prevent a vehicle from crashing through them. Cameras (CCTV) can be used to monitor fence lines.

Gates may be mechanically locked, or electronically locked and monitored using remote control equipment.

Guard stations and controlled access points should be considered if the facility has an unusual amount of personnel traffic such as during major construction or maintenance periods. Personnel entering or leaving should be logged so that a record of those on-site is maintained for both security and safety reasons.

Any personnel entering the facility shall be identified and enter through a controlled point. Motion detectors, door alarms, and gate alarms may be used to detect intruders. These systems are particularly valuable if the facility is unmanned at times.

9.8.4 Emergency Assembly Area

A designated assembly area should be identified for employees, visitors, and contractors to proceed to in the event of an emergency. The location of this Emergency Assembly Area should be identified to all employees, visitors, and contractors on site prior to beginning any work.

9.8.5 Visitors and Contractors

Sign-in sheets may be used to track any contractors and visitors on site in case an emergency arises. Contractors should be oriented to the facility safety requirements and procedures prior to performing any work on site.

9.8.6 CCTV

Where available, security cameras should be used to provide real time and recorded visual monitoring of cavern wellhead, building entrances, gates, fences, and other strategic locations. Not only can they alert
an operator of a real time security or safety issue, they can provide valuable information during post incident review.

9.8.7 Plant Communications

Storage facilities should have a means of communication and/or an alert system for operations personnel using intrinsically safe devices. This can include a phone system, radios, pagers.

9.8.8 Personal Protective Equipment (PPE)

Employees should be provided with the safety equipment necessary to safely perform the tasks assigned. This can include but is not limited to hard hats, safety glasses, hearing protections, gloves designed for the task at hand, steel toed shoes, and flame retardant clothing.

9.8.9 Lockout and Tagout Systems

Lockout and tagout (LOTO) systems shall be used at storage facilities to protect workers from hazardous energy sources. A LOTO procedure shall be developed for each cavern wellhead to allow for calibration, maintenance and workovers.

9.8.10 Man-Down Systems

A man-down system should be used if a facility is manned by a single person at times. They can alert company and emergency responders to an injury or illness that requires immediate action and the need to call out replacement operators.

9.8.11 Well Identification

Permanent signs identifying the well and storage facility name, owner, and contact telephone number should be installed and clearly visible.

9.8.12 Barriers

Barriers should be installed around wellheads and other critical facilities to prevent accidental or intentional damage by vehicles and equipment. These barriers should be removable to provide space for maintenance or workover equipment.

9.9 Operating Administration

9.9.1 Procedures

All operators shall have operation and maintenance (O&M) procedures. These procedures should allow for the safe operation and necessary maintenance of the wellhead and cavern to ensure integrity. Operators should have specific procedures for caverns and wellheads that include routine operation and maintenance guidelines as well as workover and emergency procedures.

The list below includes some of the procedures that should be developed as part of a comprehensive O&M manual.

— emergency procedures;
— mechanical integrity testing;
— ESD system testing;
— general workover procedures (specific workover procedures developed as needed);
— instrumentation testing and calibration;
— periodic wellhead and wellhead valve inspections.

9.9.2 Emergency Plans and Procedures

9.9.2.1 General

Operators shall develop emergency response plans to provide for the safe control or shutdown of the storage facility, including the storage caverns, in the event of a failure or other emergency condition. The safety of company personnel and the public should be the primary objective of the plan. Most emergency
plans should include the following components:
— Incident Command Structure;
— communication guidelines and communications;
— evacuation procedures;
— provide for safe shutdown;
— provide for safety of company personnel and the public;
— emergency drills.

9.9.2.2 Annual Review
The plan should be reviewed at least annually and tested for effectiveness using annual emergency drills.

9.9.3 Blowout Contingency Plan
The uncontrolled release of product from a liquid hydrocarbon storage cavern should be addressed either in the Emergency Response Plan or in a separate Blowout Contingency Plan.

9.9.4 Records
Records documenting cavern system development, operations and maintenance should be maintained as required by regulatory authorities. The general records activity can be divided into five categories.

9.9.4.1 Design and Construction Records
Drilling and completion reports, geology structures/mapping, and sonar logs. It is recommended that all facility modifications, revisions, and additions be promptly updated to the files and all design data, drawings and equipment documents be kept current and show all changes.

9.9.4.2 Regulatory Compliance Records
The operator/owner shall retain all necessary permits and records as required by regulatory authorities.

9.9.4.3 Maintenance Records
Maintenance requirements for each underground storage facilities may vary, depending on operator requirements and local regulation.

9.9.4.4 Ongoing Operations Records
All operators/owners shall keep any record that shows overall condition and performance of the facility: a typical cavern operating report with required information such as well number, working capacity, product movement in or out, maximum/minimum operating/working pressures etc. In addition, all underground storage well product and brine pressures should be monitored and recorded on a routine basis.

9.9.4.5 Operations Log Book
It is recommended that all operators establish an operations log book. Any activities/events such as cavern condition and performance that appears to be abnormal should be documented in the book.

9.9.5 Training

9.9.5.1 General
Training programs are valuable tools in the ongoing development of employees to ensure that they have the knowledge and skills necessary to perform their duties safely. These programs can take the form of manuals, on-the- job training and computer based training. Training programs should address routine operations, but should also address possible abnormal operations and emergency conditions. Training programs should be reviewed periodically to measure the effectiveness of the program.

9.9.5.2 On-the-Job Training
On-the-job training can be an effective method of training inexperienced employees. Any on-the-job
program should include a review through interview and hands on demonstration to ensure the required knowledge has been acquired.

NOTE  There are many industry associations and organizations that can provide valuable training opportunities. This training can take the forms of roundtable meetings, seminars, and workshops.

10 Cavern Integrity Monitoring

10.1 General

Functional integrity is a critical goal of the design and construction of the cavern system. Once in operation and throughout its life, the cavern system shall be monitored to ensure the continuance of functional integrity. Table 1 provides a list of integrity monitoring methods.

Table 1—Integrity Monitoring Methods

<table>
<thead>
<tr>
<th>Method Name</th>
<th>Type of Test</th>
<th>General Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavern System Scope</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical Integrity Test: Liquid Filled</td>
<td>Containment Test</td>
<td>Wireline pressure and temperature gauges are lowered into the cavern on two separate dates. Cavern liquid volume is calculated from data acquired on each log run and the difference in volume is assessed against pass/fail criteria. Requires: liquid-filled cavern at MAOP, known cavern size Opportunities: when cavern is at MAOP and has been shut in for a suitable time.</td>
</tr>
<tr>
<td>Pressure Observation Test</td>
<td>Containment Test</td>
<td>Product and brine pressure is monitored at the surface. A product cap is placed in the cavern such that the product brine interface is below the casing seat. The cavern is pre-pressured with brine and then pressurized to MAOP plus a percentage (5 to 10% for example) and the pressure monitored for a period of time. During the monitoring phase the cavern may be repressured such that there are several pressure drop observation cycles. A leak rate is determined based on the bbls/psi pressure ratio obtained during the brine prepressure and the last part of the test (last 48 hours for example). Requires: no flow Opportunities: during normal operations or following workover</td>
</tr>
<tr>
<td>Inventory Verification Analysis</td>
<td>Containment Assessment</td>
<td>All products injected into or withdrawn from a storage cavern should be metered using industry-accepted standards. Measurement devices should be calibrated and inspected on a regular basis. When a cavern is emptied, gains and losses, other than those reasonably attributed to measurement inaccuracy, should be investigated for cause. It is also possible to run a density log to determine the product level in the cavern. The volume is then calculated based on the most recent sonar survey and compared to measured volumes. Gains and losses, other than those reasonably attributed to measurement inaccuracy, should be investigated for cause. Requires: product over brine-filled cavern, no flow Opportunities: during normal operations, following an interface log</td>
</tr>
<tr>
<td>Mechanical Integrity Test: Nitrogen/Brine Interface</td>
<td>Casing Seat Containment Test</td>
<td>Nitrogen gas is injected into a brine-filled cavern to below the casing seat. Movement of the nitrogen-to-brine interface is monitored by wireline log. The ending amount of nitrogen is compared to the starting amount and assessed against pass/fail criteria. Requires: brine-filled cavern Opportunities: at end of solution mining, following workovers, or during testing when the cavern is de-inventoried.</td>
</tr>
<tr>
<td>Mechanical Casing Seat</td>
<td>Nitrogen gas is injected into a product over brine-filled cavern to below the</td>
<td></td>
</tr>
<tr>
<td>Integrity Test: Nitrogen/Product Interface</td>
<td>Containment Test</td>
<td>casing seat. Movement of the nitrogen-to-product interface is monitored by wireline log. The ending amount of nitrogen is compared to the starting amount and assessed against pass/fail criteria. Requires: product over brine-filled cavern Opportunities: during normal operations or following workover</td>
</tr>
<tr>
<td>Mechanical Integrity Test: Casing Seat Containment Test</td>
<td>Liquid product is injected into a brine-filled cavern to below the casing seat. Movement of the product-to-brine interface is monitored by wireline log. The ending interface level and well pressure is compared to the starting values and assessed against pass/fail criteria. Requires: product over brine-filled cavern Opportunities: following workover</td>
<td></td>
</tr>
<tr>
<td>Caliper Log</td>
<td>Casing Assessment</td>
<td>Measures last cemented casing string geometries including internal diameter and ovality. Requires: no hanging string be present. Opportunities: available during workovers in which the brine string is removed.</td>
</tr>
<tr>
<td>Magnetic Flux Leakage Log</td>
<td>Casing Assessment</td>
<td>Measures last cemented casing string for corrosion characteristics including pits and defects. Requires: no hanging string be present, casing size less than 24 inches. Opportunities: available during workovers in which the brine string is removed.</td>
</tr>
<tr>
<td>Electro-magnetic Log</td>
<td>Casing Assessment</td>
<td>Measures last cemented casing string for corrosion characteristics including pits and defects. Requires: no flow Opportunities: may be run through hanging string</td>
</tr>
<tr>
<td>Ultrasonic Log</td>
<td>Casing Assessment</td>
<td>Measures last cemented casing string for corrosion characteristics including pits and defects. Requires: no flow; hanging string removed Opportunities: available during workovers</td>
</tr>
<tr>
<td>Temperature Log</td>
<td>Casing Assessment</td>
<td>Measures temperature in the wellbore. Temperature generally increases with depth due to natural geothermal heating. Deviations from expected trends can be an indication of a leak. Requires: product over brine-filled cavern, no flow Opportunities: available during normal cavern operations.</td>
</tr>
<tr>
<td>Cement Bond Log</td>
<td>Relative Measure of Quality of Cement Bond</td>
<td>Measures a relative degree of cement bond surrounding the last cemented casing by way of the attenuation of an acoustic signal. Requires: no hanging string present, with liquid filled wellbore. Opportunities: after drilling or during workover operations</td>
</tr>
<tr>
<td>Downhole Camera</td>
<td>Casing Assessment</td>
<td>Provides multiple single-frame or full-motion video of the condition of the inside of the wellbore. Requires: clear liquid or gas. Opportunities: no hanging string present, with liquid filled wellbore.</td>
</tr>
</tbody>
</table>

Cavern Scope
<table>
<thead>
<tr>
<th>Method</th>
<th>Assessment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonar Survey</td>
<td>Cavern Shape Assessment</td>
<td>Uses sonar survey techniques (sonic wave generation and return time) to measure distances to cavern walls. Produces cavern shape and size measurements. Requires: no flow Opportunities: may be run with or without hanging string removed. NOTE: Verify with your sonar tool provider to verify the tool will work with the hanging string(s) being used.</td>
</tr>
<tr>
<td>Cavern Total Depth Log</td>
<td>Cavern Floor Assessment</td>
<td>The bottom of the cavern is “tagged” by way of running a wireline tool with depth measurement into the cavern. Repeated runs over time can help assess floor movements, salt falls and wall slumps. When an interface tool is attached, the depth to the product/brine interface can be determined and the hanging string depth(s) can be verified. Requires: an open pathway for logging tool to the bottom of the cavern. Opportunities: available during normal cavern operations.</td>
</tr>
<tr>
<td>Subsidence Monitoring</td>
<td>Ground Subsidence Assessment</td>
<td>Using surface elevation survey techniques, any subsidence in the area above and near the cavern can be monitored. Requires: access to suitable surface locations. Opportunities: anytime.</td>
</tr>
<tr>
<td>Wellhead Scope</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultrasonic Thickness Measurements</td>
<td>Remaining Strength Assessment</td>
<td>Using ultrasonic measurement tools, the wall thickness of key areas of wellhead valves and fittings can be monitored. Repeated measurements can help assess wall loss due to corrosion or erosion effects. Requires: marked locations for repeated measurements. Opportunities: anytime.</td>
</tr>
<tr>
<td>Cemented Annuli Pressure</td>
<td>Casing and Casing Seat Assessment</td>
<td>Pressure may be present in the cemented annuli within the wellhead for a number of reasons. Monitoring the pressure on these annuli can help monitor for unexpected changes. Requires: access on the wellhead to the annuli for pressure gauges. Opportunities: anytime.</td>
</tr>
</tbody>
</table>

10.2 Holistic and Comprehensive Approach

It is important to note that there is no one best or preferred method of monitoring the cavern system integrity. Therefore, each operator shall take a holistic and comprehensive approach to monitoring cavern integrity, which includes the following aspects of design, monitoring, and engineering evaluation.

— A best practice design based on individual cavern system configuration.
— Identification and assessment of risks to functional integrity.
— The use of multiple monitoring methods.
— An approach that seeks every opportunity to conduct integrity monitoring inspections, not just on a set planned frequency, but also when other well work or facility outage allows for accelerated monitoring inspections.

10.3 Integrity Monitoring Program

The outcome of this holistic and comprehensive approach shall be a formal written Integrity Monitoring Program that shall contain, at a minimum, the following components:

— identification of cavern system components to be monitored;
— monitoring methods specifying:
10.4 Review of Integrity Monitoring Methods

Table 1 lists monitoring methods currently in use by salt cavern operators. Each operator shall evaluate these methods for applicability and inclusion in their Integrity Monitoring Program. These methods are found in Annex B.

10.5 Inactive Caverns

Caverns that are not in active storage service shall be monitored to prevent over pressure due to creep closure. For this monitoring, it is typical for all hydrocarbon liquids, except for that needed to maintain roof blanket, to be removed from the cavern. Filling the brine string with fresh water to prevent salting should be considered. Product and brine pressures should be monitored and recorded at least weekly and a log maintained to note the date and volume of all activities, such as brine removal to relieve pressure due to creep closure or fresh water injection to dissolve salt buildup. All anomalous readings should be investigated and explained. If regulations allow, the ongoing pressure monitoring may be performed in lieu of an MIT. Additional measures such as disconnecting hydrocarbon flowlines and periodic reporting may be required.

11 Cavern Abandonment

11.1 Objectives

The objectives of cavern abandonment are to stabilize the cavern and maintain its hydraulic integrity for the long term.

11.2 Abandonment Design

As of this writing, there is no industry consensus for specific procedures for abandoning a salt storage cavern. However, there is a general understanding in the industry of issues and factors that must be considered when designing a cavern-specific abandonment procedure. The issues in cavern abandonment have been identified through research projects of the Solution Mining Research Institute (SMRI) that resulted in a comprehensive abandonment theory. This research later prompted several field demonstration projects to explore the cavern abandonment theory. Two projects for relatively shallow caverns were completed in 2009 [11] and 2011 [11b] and one project for deep caverns was completed in 2015 [11c]. Major questions remain concerning the length of time required for brine temperature equalization with the salt formation temperature prior to sealing and abandonment.

Most attempts at abandonment have followed the methods used to abandon exploration and production or disposal wells, e.g. the setting of a series of cement plugs across significant zones in the well, such as salt/caprock interface and potable water sands. One innovative abandonment design for domal salt caverns includes perforating the production casing above salt (in the porous caprock) and setting a tail pipe below the roof to prevent any hydrocarbon escape. As pressure in the cavern builds, brine is believed to move up hole and be released through the perforations into the zone above the salt.

Other operators prepare the caverns for continuous monitoring rather than attempting abandonment. Certain steps as listed below should be taken prior to abandonment. These steps can provide the basis for analysis of future cavern integrity.

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2 Some of the early research is summarized in [10]
11.3 Removal of Stored Product
The cavern shall be evacuated, to the extent practicable, of product by the displacement of the stored product with saturated brine during abandonment operations.

11.4 Wellbore Integrity Test
A wellbore mechanical integrity test or other method of determining integrity, including continuous monitoring should be performed after removal of the stored product when a cavern is being abandoned.

11.5 Removal of Downhole Equipment
All downhole equipment and hanging strings should be removed from the cavern and wellbore prior to abandonment.

11.6 Production Casing Inspection
A full inspection of the production casing should be made (see 8.7.4).

11.7 Sonar Survey
A sonar survey should be conducted to determine the final shape and areal extent of the cavern.

12 Risk Management for Liquid Hydrocarbon Storage Operations

12.1 General
This section addresses risk management for solution mined liquids storage caverns including the cavern, wellhead, and first ESD valve but excluding facility piping past the first ESD valve. Risk is defined as the consequence of a realized threat multiplied by the likelihood of its occurrence.

12.2 Risk Management
The operator should develop, implement, and document a program to manage risk that includes data collection, identification of potential threats and hazards to the storage operation, risk analysis including estimation of the likelihood of occurrence of events related to each threat, the likelihood of occurrence and potential severity of the consequences of such events, and the preventive, mitigative, and monitoring processes to reduce the likelihood of occurrence and/or the likelihood and severity of consequences, and a periodic review and reassessment of the processes.

12.3 Data Collection and Integration

12.3.1 General
Identifying and collecting the information relevant to a storage field is part of risk management. Data review and integration can highlight conditions in need of attention or additional information collection, assist in threat and hazard identification and risk analysis, and contribute to the continual improvement process.

12.3.2 Data Sources
The operator should use available information such as performance data collected through the cavern history, operations and maintenance (O&M) activities, geotechnical data such as well logs, engineering data, assessment data, and completion reports to determine susceptibility to threat and hazard-related events and to assess threat and hazard interaction.

12.4 Threat and Hazard Identification and Analysis

12.4.1 General
A hazard is a situation or condition that has the potential to cause loss, damage, or harm to a storage cavern, well, or well site and thus affects the functional integrity of the storage operation. A threat to storage functional integrity can be created by an encounter with or an activation of a hazard in the course of the storage operation. The operator may determine that some storage facilities are not susceptible to specific threats based on existing information, in which case the operator can provide justification and
documentation for the exclusion of a specific threat. A lack of data or information should not be used as justification to exclude a specific threat.

12.4.2 Methodology

The operator should evaluate the potential threats and hazards impacting storage caverns and wells. The operator should refer to the sample list of common threats and hazards in Table 1. Table 1 is not a complete list of threats and hazards associated with underground storage of liquids in salt and operators may supplement the list in Table 1 with other hazards or threats identified by site-specific assessments.

The operator should assess risk from potential events that could occur related to potential threats and hazards to individual facilities, such as wells, and by region when considering the reservoir.

The operator should assess potential threat and/or hazard interaction, such as the relationship of the threat of casing damage during well drilling or service work that could exacerbate corrosion processes.

12.5 Preventive & Mitigative (P&M) Measures

12.5.1 General

P&M measures are actions conducted by the operator to reduce the risks to the storage facilities by reducing the likelihood (preventive) or reducing the consequence (mitigative) of events related to the threats identified in 8.4. The P&M measures include routine condition monitoring activities since the acquisition and analysis of data provides information upon which additional measures can be implemented. Table 1 presents a sample list of programs, methods, or tools commonly employed by operators to monitor and manage risks. Table 1 is not a complete list of potential P&M measures and operators may supplement the list in Table 1 with other P&M measures identified by site-specific assessments.

12.5.2 Methodology

The operator should develop P&M measures to manage risks.

The operator should review the P&M measures listed in Table 1 to determine those measures that manage risks based on site-specific conditions. Not all risks need a P&M measure if the level of risk is fully acceptable or if it is not necessary to reduce risk by further efforts.

The operator should employ the effective P&M measures and train their personnel on the procedures related to the P&M measures. The operator may apply these P&M measures to individual wells, individual facilities, and/or groups of wells or facilities.
<table>
<thead>
<tr>
<th>Category of Review</th>
<th>Threat or Hazard</th>
<th>Threat/Hazard Description</th>
<th>Potential Consequences</th>
<th>P&amp;M Programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wells</td>
<td>Well integrity (corrosion, material defects, erosion, equipment failure, annular flow)</td>
<td>Product containment failure due to inadequately sealed storage well(s), e.g. casing corrosion, cement bond failure, material defect, valve failure, gasket failure, thread leaks, etc.</td>
<td>- Loss of stored product inventory&lt;br&gt; - Damage to well site facilities and equipment&lt;br&gt; - Safety hazard to company personnel and the public&lt;br&gt; - Loss of use of water sources and/or wells&lt;br&gt; - Loss of storage cavern utility</td>
<td>- Casing condition and inspection program&lt;br&gt; - Monitoring pressure, rate and inventory&lt;br&gt; - Cement analysis and evaluation&lt;br&gt; - Internal corrosion monitoring&lt;br&gt; - Plugged and abandoned well review and surveillance&lt;br&gt; - Monitor annular pressures,&lt;br&gt; - surface shut-off valves&lt;br&gt; - Monitor cathodic protection as applicable.&lt;br&gt; - Operate, maintain, and inspect valves and other components</td>
</tr>
<tr>
<td>Design</td>
<td>Design</td>
<td>Product containment failure due to inadequately completed wells, failure of cement stage tool, pressure rating of components, etc.</td>
<td>- Damage to well site facilities and equipment&lt;br&gt; - Safety hazard to company personnel and the public&lt;br&gt; - Loss of use of water sources and/or wells&lt;br&gt; - Loss of stored product inventory&lt;br&gt; - Loss of storage cavern utility</td>
<td>- Collect and evaluate plugged and abandoned well records and rework or plug as necessary&lt;br&gt; - Develop design standards for new wells&lt;br&gt; - Evaluate current completion of existing wells for functional integrity and determine if remediation monitoring is required</td>
</tr>
<tr>
<td>Operation &amp; maintenance activities</td>
<td>- Inadequate procedures&lt;br&gt; - Failure to follow procedures&lt;br&gt; - Inadequate training&lt;br&gt; - Inexperienced personnel and/ or supervision</td>
<td></td>
<td>- Loss of stored product inventory&lt;br&gt; - Damage to well site facilities and equipment&lt;br&gt; - Safety hazard to company personnel and the public&lt;br&gt; - Loss of use of water sources</td>
<td>- Procedures&lt;br&gt; - Training of personnel and contractors and establishment of procedures</td>
</tr>
<tr>
<td>Well intervention</td>
<td>Equipment Failure During Drilling or Workover</td>
<td>Product containment failure during snubbing job</td>
<td>Trapped product release during workover (belch)</td>
<td>Third-party damage (intentional/unintentional damage)</td>
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<tr>
<td>and/or wells</td>
<td>- Damage to drilling rig or service rig</td>
<td>- Hazard to operator and service company personnel on well site</td>
<td>- Hazard to operator and service company personnel on well site</td>
<td>- Loss of storage cavern utility</td>
</tr>
<tr>
<td></td>
<td>- Loss of tools in wellbore</td>
<td>- Safety hazard to public</td>
<td>- Safety hazard to public</td>
<td>- Impact to service reliability</td>
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<tr>
<td></td>
<td>- Hazard to operator and service company personnel on well site</td>
<td>- Damage to drilling rig or service rig</td>
<td>- Damage to service rig</td>
<td>- Damage to well site facilities and equipment</td>
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<td>- Loss of storage cavern utility</td>
<td>- Loss of stored product inventory</td>
<td>- Loss of stored product inventory</td>
<td>- Safety hazard to company personnel and the public</td>
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<td></td>
<td>- Loss of brine</td>
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<td>- Loss of stored product inventory</td>
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<td></td>
<td>Surface and subsurface setback requirements from storage wells and well sites for both vertical and lateral buffer zones</td>
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<tr>
<td>Outside force – natural causes</td>
<td>Weather related and ground movement (heavy rains, floods, lightning, earth movements, groundwater table changes, subsidence, etc.)</td>
<td>Damage to facilities/impact to service reliability</td>
<td>Subsidence monitoring, Perform routine patrols and surveillance, and event-specific surveillance activities</td>
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<tr>
<td>Third-party damage (third-party well operations)</td>
<td>Third-party drilling storage and leaching activities</td>
<td>Loss of storage cavern utility, Loss of stored product inventory, Damage to third-party/public property, Hazard to personnel and public safety, Safety hazard if operating pressure of adjacent storage caverns are not similar to the storage pressure of a third party cavern</td>
<td>Promote development of rules and regulations for the protection of storage from third-party oil and gas development, Surface and subsurface setback requirements from storage wells</td>
<td></td>
</tr>
<tr>
<td>Cavern</td>
<td>Uncertainty of salt boundaries and zones of preferential dissolution</td>
<td>Liquids migration beyond salt cavern boundary</td>
<td>Collect and review existing regional geological studies and data, Acquire geological data from previously drilled penetrations in or around the salt from oil and gas wells, disposal wells, storage wells, etc., Acquire new data (e.g., electric logs, new wells, core, seismic, well testing, tracer gas studies, etc.)</td>
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<tr>
<td>Geologic uncertainty</td>
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<tr>
<td>Subsidence</td>
<td>Loss of storage cavern utility, Damage to surface piping, equipment, and third party/public property</td>
<td>Subsidence monitoring, Perform routine patrols and surveillance, and event-specific surveillance activities</td>
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<tr>
<td>Failure of caprock</td>
<td>Loss of salt dome</td>
<td>Operating</td>
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<tr>
<td>Surface</td>
<td>Store fluid compatibility issues</td>
<td>Intentional/unintentional damage</td>
<td>Outside force—natural causes</td>
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<td></td>
<td>Stored fluid compatibility issues</td>
<td>Storage of reactive or corrosive fluids.</td>
<td>Weather related and ground movement—Heavy rains, floods, lightning, earth movements, groundwater table changes, subsidence, etc</td>
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<td>- Loss of storage cavern utility</td>
<td>- Wellbore damage caused by uncontrolled chemical reactions down hole.</td>
<td>- damage to facilities</td>
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<td>- Damage to third-party/public property</td>
<td>- Loss of salt dome integrity</td>
<td>- impact to service reliability</td>
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<td></td>
<td>- Hazard to personnel and public safety</td>
<td>- Loss of storage cavern utility.</td>
<td>- Perform routine patrols and surveillance, and event-specific surveillance activities</td>
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<td>procedures and limits</td>
<td>- Internal corrosion that could result in a degradation to well casing and/or facility piping.</td>
<td>- Develop design specifications (e.g. barriers to deflect flood</td>
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<tr>
<td></td>
<td>- Well design</td>
<td>- Review the fluid properties and determine compatibility of the fluid to be stored in salt and under pressure.</td>
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<td></td>
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<td>- Conduct internal corrosion studies and evaluate mitigation programs as needed</td>
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<td>- Install protection equipment (e.g. fences, alarms, etc.) for site security and safety</td>
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<td>- Include storage facilities into the corporate security plans</td>
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<td>- Develop storage well blowout contingency plan</td>
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<td>- Liaison with law enforcement agencies</td>
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<td></td>
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<td>- 811 Call-Before-You-Dig programs (damage prevention program)</td>
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<tr>
<td></td>
<td></td>
<td>- Perform routine patrols and surveillance, and event-specific surveillance activities</td>
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<td></td>
<td></td>
<td>- Develop design specifications (e.g. barriers to deflect flood</td>
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</tbody>
</table>
12.6  Risk Assessment

12.6.1  General

Risk assessment uses tools and techniques that evaluate and prioritize risks to direct risk management activities toward promoting functional integrity of the storage operation.

12.6.2  Methodology

The operator should assess risk related to the storage operation using a consistent process. The operator should determine the risk assessment method applicable for the facilities. A risk assessment method should include the following characteristics in the risk assessment protocol:

a)  identification of potential threats and hazards to a storage facility;
b)  evaluation of likelihood of events and consequences related to the events;
c)  develop preventive and mitigating measures to monitor and/or reduce risk;
d)  documentation of risk evaluation and decision basis for preventive and mitigative (P&M) measures;
e)  provision for data feedback and validation; and
f)  regular, periodic risk assessment reviews to update information and evaluate risk management effectiveness.

The operator should review the results of the risk assessment to determine whether the risk assessment, resulting prioritization, or ranking represents its facilities and characterizes the risks. Review may be performed by personnel familiar with storage operations, risk management, and methods of analyzing risk and results.
12.7 Periodic Review and Reassessment

12.7.1 General
The operator should assess the effectiveness of risk monitoring and risk management programs and maintain a continual review and improvement cycle in risk management activities to provide functional integrity of the storage operation. The interval of review and reassessment should be short enough to identify operational and monitoring trends and measure the effectiveness of P&M measures, but long enough that the data and information that can be brought into the analysis are meaningful.

12.7.2 Frequency
The operator should define a review frequency for the risk assessment and perform a review and update of the risk assessment in accordance with the defined frequency.

12.7.3 New Threats and Hazards
If during the course of operations new threats or hazards are identified, or the impact of threats or hazards changes markedly, the operator shall assess the risk associated with new conditions and evaluate and prioritize risk management options in accordance with the risk assessment.

12.7.4 Procedures
The operator should develop procedures that define the data or information to be reviewed, and methods of data trending or normalization in the context of the risk assessment, by analyzing such factors as integrity performance and the number and types of issues that are occurring, as well as other conditions that might trigger an evaluation at a shorter frequency (e.g. new encroachments, third-party drilling, third-party damage).

12.7.5 Performance Measures
The operator should determine specific performance measures to monitor and review in order to determine if risk management actions need revisions or additional P&M measures.

12.8 Recordkeeping
The operator should develop a risk management records retention schedule and management plan. The operator should define the records retention period. Risk management documentation can include data used during the risk assessment, P&M measures employed, and the periodic evaluation of performance metrics.
Annex A
(informative)
Open-hole Well Logs

A.1 General
Subsurface geologic assessment primarily relies upon open-hole well log data. Well log data provide the means to evaluate the petrophysical properties of the subsurface strata and the basic data for creating subsurface geologic maps and cross-sections. While not a comprehensive list, below are short descriptions of some useful logs run in salt cavern wells.

A.2 Gamma-Ray (GR)
GR logs measure the natural radioactivity of the formation. They are primarily used for well correlation and to identify the presence of shale or K-Mg salts, which can have detrimental impacts on the development of salt storage caverns. Without additional data, such as density or sonic logs, a GR log cannot distinguish halite from anhydrite or clean sand. A typical GR log also cannot distinguish shale from K-Mg salts. Borehole GR logs can be correlated with core gamma logs to improve core-log integration for salts having sufficient impurities to exhibit a gamma ray contrast. GR logs are useful for correlation between cased-hole and open-hole logs because they can be run in boreholes with and without casing. These logs are sensitive to borehole size changes.

A.3 Spectral Gamma-Ray
A spectral gamma ray log segregates the GR signal into components (K, Ur, and Th), potentially allowing shales to be discriminated from K-Mg salts. These logs are sensitive to borehole size changes.

A.4 Litho-density
Litho-density logs measure the photoelectric effect of the rock from which bulk density can be derived. These logs are useful for characterizing the impurity content of the salt as well as the lithology of the caprock (domal salt) and interbeds (bedded or deformed salt). The bulk density of halite derived from a density log is lower than the true bulk density of halite (i.e. halite density = 2.167 g/cc, log density for halite ~2.03 g/cc). The tool is a contact tool so it is sensitive to hole size and/or borehole irregularity.

Density logs are typically run in oil and gas exploration and are usually presented as density porosity assuming either a sandstone or limestone matrix. For salt cavern wells it is more useful to request that the data be presented as bulk density so that the lithology and impurity content of the salt can be better evaluated.

A.5 Compensated Neutron
Compensated neutron logs are porosity logs that measure the hydrogen ion concentration in the formation which is indicative of liquid-filled porosity in clean shale-free formations. They are sensitive to hole size, temperature, and salinity and require environmental correction. Interpretation charts are operator dependent and vary among logging companies. Neutron curves generally read low in gas-filled zones because of the gas effect. These logs can be used to identify gas zones in porous media when used in conjunction with a density porosity curve from a litho-density log. Neutron logs may give an indication of anomalous salt containing brine or gas.

A.6 Borehole Compensated (BHC) Sonic
BHC sonic logs are a basic type of sonic log that measures interval transit time of compressional acoustic waves (DTC). DTC is the reciprocal of velocity and is dependent upon lithology (elastic properties and density) and porosity. Sonic logs are typically used to calculate matrix porosity in clastic and carbonate rocks. The DTC of clean halite is µsec/ft. In salt cavern wells, sonic logs can give an indication of the relative amount and type of impurity content within the salt. Sonic data can also be useful for depth conversion and calibration of seismic data.
A.7 Dipole or Array Sonic

Unlike BHC sonic, which records only compressional velocity, dipole or array sonic are full waveform tools that measure the transit times of compressional, shear, and Stoneley waves. These log data can be used to determine the dynamic elastic moduli (e.g. Young’s modulus and Poisson’s ratio) of the rock along the borehole. Some tools can also measure the distance and orientation of acoustic reflectors a short distance away from the borehole.

A.8 Check Shot Surveys

In general, check shot surveys provide more reliable velocity information for calibration and verification of seismic time/depth conversions than sonic logs can provide. Check shot surveys are similar to Vertical Seismic Profiles, but the two differ in receiver density, placement, and recorder spacing.

A.9 Mud Log (Cuttings or Sample Log)

Although not a geophysical log, a mud log can provide useful lithologic information in relatively competent strata. To be valuable in salt the drilling fluid should be of sufficient salinity for the salt cuttings to survive. Formations are usually determined by first arrivals of identifiable cuttings and as such the results are influenced by mixing in the borehole, estimated bottoms-up time and cutting survivability. In addition to the lithology of the cuttings, mud logs can also include penetration rates, tight borehole, stuck pipe, lost circulation zones, and gas occurrence.

A.10 Temperature Logs

Temperature logs can be run to measure the local geothermal gradient in newly drilled cavern wells before cavern development. Temperature data can be useful for the geomechanical assessment of the salt because salt creep and deformation is temperature dependent. It is important that the temperature of the fluid in the borehole be allowed to equilibrate to in-situ conditions prior to running a temperature log.

A.11 Multi-arm Caliper

As part of the geologic site characterization, the caliper log is useful in that it can provide some qualitative information on the relative strength and dissolution characteristics of the rocks encountered. As many wireline logging tools are sensitive to borehole rugosity and bore-hole size, the caliper log can be used to quality control (QC) the wireline log data. The multi-arm caliper can also be used for cement volume calculations during the drilling operations.

A.12 Resistivity

Resistivity logs measure the ability of a formation to transmit electrical current and are a function of water saturation. Salt typically has a high resistivity and extremely limited penetration of drilling fluid, and resistivity logs alone are not of much value in salt. Resistivity logs are of more use when run above the salt where they are useful for correlation, identifying caprock and carbonates, hydrocarbon versus water-bearing zones, permeable zones, and identifying the base of groundwater. The type of resistivity log used depends upon borehole conditions. Induction logs do not work in oil-based or salt-saturated drilling muds. Laterologs should be used in salt or salt-saturated drilling mud.

A.13 Spontaneous Potential (SP)

SP logs measure the natural electric potential that arises due to differences in the ionic activities (relative salinity) of the drilling mud and the formation fluid. SP logs do not work in salt-saturated or oil-based mud. Therefore, other than indicating the presence of salt, SP logs are not useful for characterizing salt and are not typically run in salt. SP logs are useful for well correlation, identifying porous and permeable zones, and defining fresh water zones in the sediments above or adjacent to the salt.

A.14 Borehole Imaging Logs

Borehole imaging logs can provide high resolution data to assist with the identification and characterization of the geology intersecting a borehole. Borehole image log tools can either be electrical or acoustic. Selection of the proper tool depends upon the borehole conditions, geology and data.
requirements. Electrical tools measure resistivity from pads pressed against the borehole wall and the resolution is highly sensitive to borehole conditions. Electrical tools require conductive borehole fluids and are sensitive to mud filter cake development, shape, deviation, and rugosity. Resolution and borehole coverage are also influenced by logging speed and borehole size, with resolution tending to decrease as borehole size increases. Although standard electrical imaging tools can accommodate boreholes up to 21 in. diameter, they are ideally suited for boreholes from 6.0 in. to 12.25 in..

Acoustic imaging tools provide high resolution images of the borehole by emitting acoustical pulses and recording the travel time of returning pulses. The advantage of acoustic imaging tools is their applicability to different mud systems and full 360° borehole coverage. Mud additives and base fluid influence mud attenuation. Borehole acoustic tools operate best in boreholes with diameters from 4.5 in. to 13 in.. In light borehole mud, the maximum bore hole diameter is about 13 in.. Data quality can be severely affected by borehole irregularities.

Borehole imaging logs can be used to identify and determine the orientation of linear features such as fractures, bedding and faulting planes as well as information on lithofacies, bedding structures, porosity type, and unconformities. Borehole imaging logs may be used in salt to locate anomalous salt, shear zones, faults, and flow banding that may provide clues about preferential dissolution of salt prior to cavern solution mining and possible insoluble beds. Borehole imaging logs are limited to operating in light drilling fluids and are sensitive to borehole geometry. Borehole image logs work best when used in conjunction with other well log and core data.

If consecutive runs are made in an open borehole over a period of weeks or months, any observed variation can be attributed to geologic processes, such as swelling clays and salt creep. Such an interpretation requires the close integration of core data with a suitable suite of well logs.
Annex B
(normative)
Integrity Monitoring Methods

B.1 Wellbore Scope

B.1.1 General

The scope of the wellbore is the hole of varying diameters bored into the subsurface by the drilling rig using multiple diameter drill bits. For the purposes of this RP, the wellbore has three sections:

— a long section comprising most of the depth from the surface to near the cavern roof which is cased with steel casing;
— the casing seat which is the point where the steel casing ends;
— a relatively shorter uncased section of open rock previously bored by the drilling process and immediately below the casing seat.

It is important to monitor these sections for the ability to contain liquid hydrocarbon under pressure.

B.1.2 Mechanical Integrity Test: Nitrogen/Brine Interface Method

The Nitrogen/Brine Interface method MIT is a pressure test in which the cavern wellhead, wellbore and casing seat are tested for integrity and fitness of service. This MIT method is often conducted at the point of commissioning a cavern for liquid hydrocarbon service, which occurs at completion of solution mining operations. It is also suitable for an integrity test after cavern workover operations. Other test methods, including a product/brine MIT may be used, and follow similar processes. See Table 1 for more test methods.

The cavern should be pre-pressured with brine injection to reach the target test gradient at the production casing shoe. If unsaturated brine is used, additional injections and stabilizations may be required due to the additional space created in the cavern.

If pressure on the cavern exceeds targeted pre-pressure, brine should be removed to relieve the pressure. As nitrogen is injected the wellhead should be checked for leaks. Continue nitrogen injection until nitrogen reaches a point above the casing seat. Shutdown and monitor for casing leaks. The injection of nitrogen continues to bring the cavern to test pressure and to position the nitrogen/brine interface below the casing seat at which point injection is ceased.

Throughout the test, all wellhead pressures are monitored and the wellhead is checked for leaks. At the start and end of the test, the depth to the nitrogen/brine interface is determined using a suitable density measurement logging tool. The volume and mass of nitrogen can be calculated using:

— wellhead pressures converted to downhole conditions;
— nitrogen/brine interface depth measurements;
— an estimate of downhole temperatures based on brine temperatures in the hanging string; and
— the known volumes of the cased annulus and the cavern neck.

The test is evaluated by calculating the nitrogen volume at the beginning and end of the test period. The change in these volumes can be compared against a pass/fail criterion, determining integrity and fitness for liquid hydrocarbon service.

Pressure recorders should be installed on both the nitrogen and brine side wellhead outlets.

To avoid possible leak paths during the test, it is advisable to isolate the wellhead from all surface piping by installing blind or skillet flanges on the outboard wellhead valves. Wellhead pack-off flanges such as p-seals should be tested for leaks as well.
The wellhead pressure should be stable prior to starting the test or at least indicate a diminishing rate of decline. Nitrogen injection temperature should be regulated to that of the average wellbore temperature.

The profile and volume of the cavern neck below the casing seat should be determined by a previous sonar survey. Test resolution can be enhanced by positioning the nitrogen/brine interface in a known-volume section of the cavern neck.

B.1.3 Cased Hole Logs

Downhole logs are run as part of monitoring the integrity of the cavern and wellbore. The following is a list of logs that operators may run along with the purpose or how it can be used. A more complete list can be found in Table 1.

B.2.3.1 Caliper Log

A caliper log is used as part of a casing inspection program. The tool is lowered into the well and centralized then arms, from 4 to more than 80, are extended from the tool. The arms measure the distance from the tool the internal diameter of the casing. These direct measurements allow the tool to locate holes, casing wear, and other interior defects. This method only allows the interior of the casing to be inspected.

B.2.3.2 Magnetic Flux Leakage Log

Magnetic flux leakage log is a form of nondestructive testing that is used to detect corrosion or pitting in casing. A magnet of sufficient strength is used to induce a magnetic field around the steel casing. Areas of pitting or corrosion result in changes in that magnetic field that can be detected with the log. The method can be used to determine the location and magnitude of interior and exterior corrosion or pitting. Newer logs use directionally oriented rare earth magnets to also define the pit geometry so that casing integrity can be quantified. These logs are limited to smaller sizes and not typically available for the larger bore caverns.

B.2.3.3 Noise Log

Liquid leaking from a high pressure wellbore into the surrounding formation through a small hole or defect produces a high frequency noise signal. Under some wellbore conditions, a wireline conveyed noise logging tool can detect these signals. Ultrasonic leak detection tools have been used to find leaks that were undetectable by spinners, temperature logs, and traditional noise logs.

B.2.3.4 Temperature Log

Pressure and temperature logs can be used for a number of different applications, such as MITs and when a cavern is being prepared for abandonment.

B.2.3.5 Cement Integrity Log

As of the writing of this document, there are four main types of cement integrity logs: cement bond log (CBL), cement mapping log, ultrasonic cement mapping tools, and ultrasonic imaging logs (USI, RBT). Each log type should be evaluated for the specific job requirements.

B.1.4 Downhole Camera

A downhole camera provides multiple single-frame or full-motion video of the inside of the wellbore to provide an indication of the condition of the casing. Two types of downhole cameras are most often used. Run on standard conductor wireline cable, the “hawkeye” or single frame camera takes approximately one photo per second. For higher frame rate and picture quality, a full motion video camera which requires fiber optic based wireline cable can be run. Both types have a lens mounted on the end of the tool carrier with a downward looking light source. Some cameras have the ability to tilt the lens 90° from downward to sideward looking. Cameras can typically view approximately 4 ft down the wellbore, depending on conditions.

Wellbores filled with clear fluid provide the clearest inspections.

B.3 Cavern Scope
B.3.1 General
The scope of the cavern is the void created by solution mining the surrounding salt formation. Cavern scope integrity monitoring methods provide an assessment of the ability of the cavern to contain liquid hydrocarbon under pressure, often up to the MAOP.

B.3.2 Sonar Survey
Sonar surveys are used to determine the cavern’s shape and total volume.

B.3.3 Subsidence Monitoring
Using surface elevation survey techniques, subsidence in the area above and near the cavern should be monitored and compared to amounts predicted by geomechanical analysis. Subsidence is a natural process and is broad and wide-spread. Greater than predicted subsidence in a localized area near a cavern can be an indication of cavern instability.

B.4 Wellhead Scope
B.4.1 General
The wellhead scope is comprised of the wellhead valves and fittings. Wellhead scope integrity monitoring methods provide an assessment of the ability of the wellhead to contain liquid hydrocarbon under pressure, often up to the MAOP.

B.4.2 Ultrasonic Thickness Measurements
Using ultrasonic measurement tools, the wall thickness of key areas of wellhead valves and fittings can be monitored. Repeated measurements can help assess wall loss due to corrosion or erosion effects. Specific locations should be marked so measurements can be repeated and monitored.

B.4.3 Annulus Pressure Monitoring
Pressure may be present in the cemented annuli within the wellhead for a number of reasons. Monitoring the pressure on these annuli can help identify unexpected changes that require further investigation.
Appendix C
(informative)

Brine Tables

Brine tables, such as those contained in International Critical Tables, characterize the salt content of brine in terms of weight of salt per unit weight of brine, expressed as a fraction or as a percentage, over a range of specific gravities at one or more specified temperatures. The relationship between salt concentration in brine and brine specific gravity is strongly temperature-dependent. For this reason, field measurements of effluent brine specific gravity should be corrected from the flowing temperature to the base temperature used by the brine tables to avoid significant error in determining true brine concentration. The most useful available brine tables are expressed in terms of a base temperature of 60 °F (15.5 °C) for several reasons, including the following.

— 60 °F (15.5 °C) is an accepted standard in defining base density of water and other liquids
— Most hydrometers are calibrated to indicate the density of the measured fluid relative to that of water at 60 °F (15.5 °C); the specific gravity of water at 60 °F (15.5 °C) is 1.0.

The brine tables normally supply correction factors to convert specific gravity data from flowing temperature to a base temperature of 60 °F (15.5 °C).

After correcting specific gravity data for temperature, the true percent by weight of salt in the brine is determined from the brine tables. The corresponding percent by weight (wt %) of water in brine is given by:

\[ \text{wt % water in brine} = 100 - \text{wt % salt in brine} \]

The relative volume of salt to water in the effluent brine can then be determined as follows:

\[ \frac{\text{wt % of salt in brine}}{\text{wt % of water in brine}} = \frac{V_s}{V_w} \times \frac{\text{density of salt}}{\text{density of water}} \]

or

\[ \frac{V_s}{V_w} = \left( \frac{\text{wt % salt in brine}}{\text{wt % water in brine}} \right) \times \left( \frac{\text{density water}}{\text{density salt}} \right) \]

The total volume of dissolved salt is then determined by:

Where

\[ \frac{V_s}{V_w} \] is the volume of salt per unit volume of water in brine;

\[ V_{st} \] is the total volume of dissolved salt;

\[ V_{wt} \] is the total volume of injected water.

Consistent units of measurement should be used when completing the above calculations.
D.1 Static Pressure

Displacement caverns generally use concentric tubing strings to move stored product in or out and the displacement fluid out or in. During solution mining operations fresh water moves in and brine out through concentric tubing strings. Both operations create, in effect, a large U-tube for the flow and because of the differences in densities between the displacement fluid and the product (stored or produced), a manometer is created. In Figure 1, under static conditions (no flow) the pressure at point B, the product interface, is equal inside and outside the brine string. This pressure equals \( (\rho_b \times h_b) + P_c \), where \( \rho_b \) is the density of the brine, \( h_b \) is depth of the interface, and \( P_c \) is the static gauge pressure at point C. \( P_c \) is
referred to as the brine wellhead pressure. It also equals \((d_p \times h_p) + P_a\), where \(d_p\) is the density of the product, and \(P_a\) equals the gauge pressure at point A. \(P_a\) is referred to as product wellhead pressure. By setting these equally, the static wellhead product pressure can be established as follows:

\[
P_a = (d_b - d_p) \times h_p + P_c
\]

where
- \(P_a\) is the product wellhead pressure at point A;
- \(d_b\) is the density of brine;
- \(d_p\) is the density of product;
- \(h_p\) is the depth of interface;
- \(P_c\) is the static gauge pressure at point C.

It follows then that the static wellhead pressure of a cavern empty of product is determined by:

\[
P_e = (d_b - d_p) \times h_t + P_c
\]

where
- \(P_e\) is the static wellhead pressure for a cavern empty of product at point A;
- \(d_b\) is the density of brine;
- \(d_p\) is the density of product;
- \(h_t\) is the depth to top of cavern;
- \(P_c\) is the static gauge pressure at point C.

and a cavern full of product is determined by:

\[
P_f = (d_b - d_p) \times h_b + P_c
\]

where
- \(P_f\) is the static wellhead pressure for a cavern full of product at point A;
- \(d_b\) is the density of brine;
- \(d_p\) is the density of product;
- \(h_b\) is the depth to bottom of brine string;
- \(P_c\) is the static gauge pressure at point C.

Compressible fluids complicate this otherwise straightforward pressure calculation. For example, the density of a 3000 ft (1000 m) column of ethylene varies considerably from top to bottom, and the mean density must be calculated by iteration. Uncertain and changing product temperatures also reduce the accuracy of such wellhead pressure calculations. The accuracy of the wellhead pressure calculation is dependent on variations in brine gravity and product temperature such that calculated wellhead pressure more accurately should be given as a range for compressible fluids.

**D.2 Flowing Pressure Drop**
D.2.1 General

The displacement cavern tubing strings form a U-tube with displacement medium in one leg and stored product in at least part of the other leg. Flowing pressure drop is associated with cavern tubing strings and requires calculation of the drops in both legs of the U-tube. The common tubing string configuration involves one or two tubing strings hung concentrically within a casing cemented into the salt.

Flow in one leg, therefore, will be annular flow that is calculated via the method shown in D.2.2. The brine leg calculation involves a straight pipe pressure drop determination. For multitubing wells, the calculations involve parallel pipe flow.

As with any line sizing determination, operating cost (power) should be compared against initial capital cost (pipe size). With cavern tubing strings, the cost to drill and install larger tubing and casing increases with increased diameter. Cost data to drill and install various size tubing strings are typically evaluated to determine the most cost effective configuration.

Once the size of the cemented tubing string is determined, the sizing of the tubing string can be optimized. The cross-sectional flow area for the brine string generally will be greater than the annular section because of the higher brine gravity, viscosity, and extra pipe length, and because salt will tend to deposit on the brine string. During product filling operations, tubing strings act like an elongated shell-and-tube heat exchanger as the cool product exchanges heat with the earth-heated brine. As the brine cools and becomes supersaturated, the salt deposits on the inner walls of the brine string, reducing the cross-sectional areas and increasing the roughness factor. This leads to increasing pressure drop and, if not occasionally (or periodically) flushed with fresh water, eventually leads to salt bridges that block the flow. Oversizing the brine string flow area relative to the product flow area helps compensate for the higher true flow rates, particularly where cavern fill rates are critical.

When plotting cavern flow rates into a cavern against product wellhead pressure, a system curve typical of a piping system is generated. A plot of flow out of a cavern is similar to a centrifugal pump curve, reflecting the energy storage feature of a cavern. Generating curves similar to those shown in Figure D.2 developed in D.2.3 is required to design injection and shipping pumps and connecting pipelines.

Section D.2.3 provides an example of pressure drop calculations.

The same hydraulic considerations discussed above govern operating storage cavities and brine production (including source well and cavities being solution mined for storage). The primary differences in brine production are as follows.

a) An insoluble solution-mining cap (usually fuel oil) must be maintained.

b) The solution-mining water is usually injected down the annular space, and the brine returns up the brine string. The solution-mining cap is usually maintained via the annular space between the cemented production casing and the largest hung string, thus reducing the available flow area for fresh water and brine.

Cavern tubing strings 20 in. (50.8 cm) and smaller are typically selected in accordance with API standards for casing. Wellbore tubing strings larger than 20 in. (50.8 cm), and all surface-flow line piping are selected in accordance with API standards for line pipe.

The pressure drop across the wellhead itself is not included in the above discussion. Proper selection of the wellhead must consider the pressure drop, and hydraulic calculations must account for these losses in the calculation.

D.2.2 Sample Problem—Establishing Cavern Depth and Tubing String Sizes

The following is the pressure drop calculation for an ethylene salt dome storage cavern.

Known Information:

a) required storage capacity = 100 million pounds (MM lbs);

b) maximum flow rate into storage = 100,000 pounds per hour (lbs/hr);
c) maximum flow rate out of storage = 100,000 pounds per hour (lbs/hr);

d) cavern temperatures = 90 °F to 120 °F;

e) brine temperatures: 50 °F to 90 °F;

f) pipeline ethylene temperatures = 50 °F to 80 °F;

g) brine gravity = 1.18.

Assume the producing plant’s pumps can deliver 1700 pounds per square inch gauge (psig) at 100,000 lbs/hr hour at the wellhead. Also, assume the highest rate case consuming plant or plants require a minimum delivery pressure at the wellhead of 1300 psig at 100,000 lbs/hr.

Look at cavern depth, average diameter, and pressure drops, assuming 13 5/8 in. outside diameter with 0.480 in. wall thickness final cemented string and assuming no storage pumps or compressors will be required.

**Step 1:** Roughly calculate the depth of the cavern, assuming 100 psig flowing loss in tubing strings, as follows.

a) Empty cavern (top of cavern). A wellhead pressure of 1300 psig flowing or 1350 psig static ($P_e$) is needed on the product side. Assume 50 psig static ($P_c$) on the brine side of the wellhead.

$$P_e = (d_b - d_p)h_t + P_c$$

or

$$h_t = \frac{P_e - P_c}{d_b - d_p}$$

where (based on Figure 1)

- $P_e$ is the static wellhead pressure for a cavern empty of product at point A (1350 psig);
- $d_b$ is the density of brine ($1.18 \times 62.4 \text{ lb/ft}^3 = 73.63 \text{ lb/ft}^3$);
- $d_p$ is the density of product (18.5 lb/ft$^3$). Assuming an average product pressure of 1600 psig and a temperature of 100 °F, the density is 18.5 lb/ft$^3$ (from the ethylene pressure enthalpy diagram);
- $h_t$ is the depth to top of cavern (to be determined);
- $P_c$ is the static gauge brine pressure at point C (50 psig);

$$h_t = \frac{(1350 \text{ psig} - 50 \text{ psig}) - (144 \text{ in.}^2 / \text{ft}^2)}{73.63 \text{ lb/ft}^3 - 18.5 \text{ lb/ft}^3}$$

$$= 3395.6 \text{ ft}$$

The approximate top of the cavern is 3400 ft.

b) Full cavern (bottom of brine string). A wellhead pressure maximum of 1700 psig flowing (to permit producer plant to pressure product into cavern in all cases) or 1750 psig static ($P_f$) on the product side is needed. Assume 50 psig static ($P_c$) on the brine side of the wellhead.

$$P_f = (d_b - d_p)h_b + P_c$$

(5)
or

\[ h_b = \frac{P_f - P_c}{d_b - d_p} \]

where (based on Figure 1)

- \( P_f \) is the static wellhead pressure for a cavern full of product at point A (1750 psig);
- \( d_b \) is the density of brine \((1.18 \times 62.4 \text{ lb/ft}^3 = 73.63 \text{ lb/ft}^3)\);
- \( d_p \) is the density of product \((20.6 \text{ lb/ft}^3)\). Assuming an average product pressure of 1923 psig based on an arithmetic average of wellhead and bottom pressures or \((1700 + 2145)/2 = 1923\). The bottom product pressure is the long column of compressible product or \(1.18 \times 0.433 \times 4200 \text{ feet} = 2145 \text{ psi}\). With a temperature of 100 °F, the density is 20.6 lb/ft³ (from the ethylene pressure enthalpy diagram);
- \( h_b \) is the depth to bottom of brine string (to be determined);
- \( P_c \) is the static gauge brine pressure at point C (50 psig);

\[ h_b = \frac{(1350 \text{ psig} - 50 \text{ psig}) - (144 \text{ in.}^2 / \text{ft}^2)}{73.63 \text{ lb/ft}^3 - 20.6 \text{ lb/ft}^3} \]

= 4616 ft.

The bottom of brine string should be no deeper than approximately 4600 ft.

From these rough calculations, the cavern can be set at a depth of approximately 3400 ft to 4600 ft and meet all the flow requirements, assuming adequately sized tubing strings are inserted.

**Step 2**: Size the cavern within the range of depths from Step 1 as follows.

Assume a cylindrical cavern with a midpoint depth of \((3400 \text{ ft} + 4600 \text{ ft})/2\) or 4000 ft. At this depth, the average pressure will be \(1.18 \times 0.433 \times 4000 \text{ ft} = 2043 \text{ psi}\). At a maximum cavern temperature of 120 °F, the product density in the cavern would be 18.51 lb/ft³. To store the 100 million pounds, the cavern must have a volume of \(100 \text{ million}/18.51 \text{ pounds per cubic foot} = 5.4 \text{ million cubic feet}\).

Assuming that the site development plan calls for development of 100-ft diameter cavities at the depth interval, the cavern must be approximately 5.4 million cubic feet/100π/4 = 687 ft top to bottom, or 700 ft (rounded for this example).

Therefore, a 100 ft diameter cavern could be developed for any 700 ft interval between 3400 ft and 4600 ft. What needs to be assessed are such items as:

a) drilling and solution-mining costs (drilling an extra 500 ft in salt can cost several days of extra rig time alone);

b) the cavern site development plan (other cavities planned at set depth intervals); and

c) future changes in hydraulic requirements (future higher delivery rate flows or pressures).

Also, consider the possibility of developing cavities below the present cavities.

In this example, the assumption will be made that these factors dictate a 100 ft diameter cavern developed between 3500 ft and 4200 ft.
**Step 3:** Verify as follows the assumed flowing pressure drop of 100 psi thru the product and brine strings. Looking at a 13 3/8 in. final cemented string, tubing string pressure drops can be investigated. Assume a 9 5/8 in. brine string.

a) Calculate the pressure drop in the product annulus at the maximum flow rate out of storage. Assume the inside diameter (ID) of the cemented string is 12.515 in. and the outside diameter (OD) of the brine string is 9.625 in. To calculate the pressure drop in the product annulus, use the Darcy-Weisbach derived formula as follows:

\[
\Delta P = \frac{0.011553 (SG) (f) (Q^2) (Y)}{X^3} \text{ psi/1000 ft}
\]

where

- \(f\) is the friction factor from Moody Diagram [with Reynolds number (RN) and relative roughness \((E/D)\) from Moody Diagram];
- \(SG\) is the specific gravity;
- \(Q\) is the flow rate in barrels per day (bbl/d);
- \(Y\) is the ID in inches of outer pipe + OD in inches of inner pipe;
- \(X\) is the ID in inches\(^2\) of outer pipe – OD in inches\(^2\) of inner pipe;

\[
\frac{E}{D} = \left(\frac{E}{0.0833}\right) \left(\frac{Y}{X}\right) = \text{relative roughness for product annulus};
\]

\[
RN = \frac{92.24 (Q)}{\text{viscosity of product in centistrokes (cSt)} (Y)}
\]

To obtain density, calculate average cavern pressure:

\[
1500 \text{ psi} + \frac{(0.433 \times 1.18 \times 3500 \text{ ft})}{2} = 1645 \text{ psi}
\]

With an assumed average temperature of 120 °F, the density is 15.4 lb/ft\(^3\) (from the ethylene pressure enthalpy diagram).

To obtain specific gravity:

\[
SG = \frac{15.4}{62.4}
\]

To convert flow rate from lb/hr to bbl/d:

\[
\frac{(100,000 \text{ lb/hr})}{15.4 \text{ lb/ft}^3} = 6500 \text{ ft}^3/\text{hr}
\]

\[
= 1157 \text{ bbl/hr} = 27.8 \text{ Mbbbl/d}
\]

\[
X = (12.515 \text{ in.})^2 - (9.625 \text{ in.})^2 = 63.98 \text{ in.}^2
\]

\[
Y = 12.515 \text{ in.} + 9.625 \text{ in.} = 22.14 \text{ in.}
\]
\[ RN = \frac{92.24(27,800 \text{ bbl/d})}{(0.026 \text{ cSt})(22.14 \text{ in.})} = 4.45 \times 10^6 \]

\[ E = 0.00015 \text{ ft for steel pipes} \]

\[ E = 0.00015 \text{ ft (22.14 in.)} \]

\[ D = 0.0833 \text{ ft/in. (63.98 in.}^2 \text{)} = 0.00062 \]

\[ f = 0.018 \text{ from Moody Diagram} \]

\[ \Delta P = \frac{0.011553(SG)(f)(Q^2)(Y)}{X^3} = \text{psi / 1000 ft} \]

\[ = \frac{0.011553(15.4/62.4)(0.018)(27,800^2)(22.14)}{(63.98)^3} \]

\[ = 3.35 \text{ psi/1000 ft} \]

For the 3500 foot product annulus, the total pressure drop is as follows:

\[ 3.35 \times 3.5 = 11.7 \text{ psig} \]

b) Calculate the pressure drop in the brine string at the maximum flow rate. Using Figure 3 (Brine String Pressure Drops) with maximum flow in thousand barrels per day (Mbbl/d), intersect the size of the brine string utilized and go across to read the psi per 1000 ft (psi/1000 ft). With 27.8 Mbbl/d and a 9 5/8 in. brine string, the brine string loss is 5.7 psi/1000 ft (see note). This results in a brine string loss of 5.7 \times 4.2 = 23.9 psig.

NOTE Two 9 5/8 in. lines are shown on Figure 3. When the line on the right side is intersected, read the pressure drop from the right range of pressure drops (10 to 100).

The total pressure drop for the product and brine string to the wellhead is (product) 11.7 + (brine) 23.9 = 35.6 psig, which is less than 100 psig used in sizing.

Therefore, investigate the use of smaller, cemented casings and product string, smaller brine string, higher flow rates, or a more shallow cavern.

**D.2.3 Sample Problem: Developing Cavern Flow Rate Versus Pressure Curve**

The following is a step-by-step solution for developing the cavern wellhead pressure versus flow rate system curve similar to that shown in Figure 2.

Assume the following crude oil storage cavern:

a) size = 1000 thousand barrels (Mbbl);

b) depth = 2000 ft \((h_1)\) to 3000 feet \((h_b)\);

c) brine gravity \((SG_b) = 1.18\);

d) crude gravity \((SG_p) = 0.85\);
e) crude viscosity = 20.5 centistokes (cSt);

f) production casing = 16 in. outside diameter (OD) and 15.01 in. inside diameter (ID);

g) brine string = 10.75 in. outside diameter (OD);

h) brine wellhead pressure \( (P_c) = 50 \) psig.

**Step 1:** Develop wellhead pressures at zero flow rate or static conditions as follows:

a) Full cavern static pressure (crude) at wellhead:

\[
P_f = (SG_b - SG_p)(h_b)(0.433) + P_c
\]

\[
= (1.18 - 0.85)(0.433)(3000 \text{ ft}) + 50 \text{ psig}
\]

\[
= 479 \text{ psig}
\]

b) Empty cavern static pressure (crude) at wellhead:
Figure D.2 – Wellhead Pressure versus Flow Rate

\[ P_e = (S_G b - S_G p)(h)(0.433) + P_c \]

\[ = (1.18 - 0.85)(0.433)(2000 \text{ ft}) + 50 \text{ psig} \]

\[ = 336 \text{ psig} \]

Step 2: Develop annulus pressure drop calculations at different flow rates as follows:

a) Assume 75,000 barrels per day (bbl/d) delivery rate:
\[ \Delta P = \frac{0.011553(\text{SG})(f)(Q^2)(Y)}{X^3} = \text{psi/1000 ft} \]

\[ X = (15.01 \text{ in.})^2 - (10.75 \text{ in.})^2 = 109.74 \text{ in.}^2 \]

\[ Y = 15.01 \text{ in.} + 10.75 \text{ in.} = 109.74 \text{ in.}^2 \]

\[ RN = \frac{92.24(75,000 \text{ bbl/d})}{(20.5 \text{ cSt})(25.76 \text{ in.})} = 13,100 \]

\[ E = 0.00015 \text{ ft for steel pipes} \]

\[ \frac{E}{D} = \frac{0.00015 \text{ ft} (25.76 \text{ in.})}{0.0833 \text{ ft/in.} (109.74 \text{ in.}^2)} = 0.00042 \]

\[ f = 0.030 \text{ from Moody Diagram} \]

\[ \Delta P = \frac{0.011553(\text{SG})(f)(Q^2)(Y)}{X^3} = \text{psi/1000 ft} \]

\[ = \frac{0.011553(0.85)(0.030)(75,000)^2 (25.76)}{(109.75)^3} \]

\[ = 32.3 \text{ psi/1000 ft} \times 2000 \text{ ft} = 65 \text{ psig} \]

b) Assume 100,000 barrels per day (bbl/d) delivery rate:

\[ RN = \frac{92.24(100,000 \text{ bbl/d})}{(20.5 \text{ cSt})(25.76 \text{ in.})} = 17,467 \]

\[ E = 0.00015 \text{ ft for steel pipes} \]

\[ \frac{E}{D} = \frac{0.00015 \text{ ft} (25.76 \text{ in.})}{0.0833 \text{ ft/in.} (109.74 \text{ in.}^2)} = 0.00042 \]

\[ f = 0.028 \text{ from Moody Diagram} \]

\[ \Delta P = \frac{0.011553(\text{SG})(f)(Q^2)(Y)}{X^3} = \text{psi/1000 ft} \]

\[ = \frac{0.011553(0.85)(0.030)(100,000)^2 (25.76)}{(109.75)^3} \]

\[ = 53.6 \text{ psi/1000 ft} \times 2000 \text{ ft} = 107 \text{ psig} \]

c) Assume 50,000 barrels per day (bbl/d) delivery rate:
\[ RN = \frac{92.24(50,000 \text{ bbl/d})}{(20.5 \text{ cSt})(25.76 \text{ in.})} = 8733 \]

\[ E = 0.00015 \text{ ft for steel pipes} \]

\[ E = \frac{0.00015 \text{ ft}(25.76 \text{ in.})}{0.0833 \text{ ft/in.}(109.74 \text{ in.}^2)} = 0.00042 \]

\[ f = 0.033 \text{ from Moody Diagram} \]

\[ \Delta P = \frac{0.011553(\text{SG})(f)(Q^2)(Y)}{X^3} = \text{psi/1000 ft} \]

\[ = \frac{0.011553(0.85)(0.030)(50,000)^2(25.76)}{(109.75)^3} = 15.8 \text{ psi/1000 ft} \times 2000 \text{ ft} = 32 \text{ psig} \]

**Step 3:** Calculate as follows the brine string pressure drop (in pounds per square inch per thousand feet) at different flow rates using the 10.75 in. brine string shown in Figure 3:

- a) at 50 Mbbl/d = 11.6 \times 3 = 34.8 or 35 psig;
- b) at 75 Mbbl/d = 25.8 \times 3 = 77.4 or 77 psig;
- c) at 100 Mbbl/d = 44 \times 3 = 132 psig.

**Step 4:** Add the crude and brine strings pressure drops for a total flowing pressure drop as follows:

- a) at 50 Mbbl/d = 32 + 35 = 67 psig;
- b) at 75 Mbbl/d = 65 + 77 = 142 psig;
- c) at 100 Mbbl/d = 107 + 132 = 239 psig.

**Step 5:** Determine the wellhead pressures in Figure 2 at different flow rates for both a full and empty cavern.

- a) For a full cavern, the wellhead pressures are as follows:
  1) static = 479 psig;
  2) at 50 Mbbl/d = 479 – 67 = 412 psig;
  3) at 75 Mbbl/d = 479 – 142 = 337 psig;
  4) at 100 Mbbl/d = 479 – 239 = 240 psig.

- b) For an empty cavern, the wellhead pressure will be:
  1) static = 336 psig;
2) at 50 Mbbl/d = 336 – 67 = 269 psig;

3) at 75 Mbbl/d = 336 – 142 = 194 psig;

4) at 100 Mbbl/d = 336 – 239 = 97 psig.

NOTE Based on Darcy–Weisbach $E = 0.0004$, heavy wall tubing strings.

Figure 3 – Brine String Pressure Drops
Bibliography


[8] API Recommended Practice 5C1, Recommended Practice for Care and Use of Casing and Tubing


[12] API Standard 1104, Welding of Pipelines and Related Facilities


[15] API Recommended Practice 5A5, Field Inspection of New Casing, Tubing, and Plain-Ended Drill Pipe

[16] API Recommended Practice 5B1, Gauging and Inspection of Casing, Tubing and Line Pipe Threads


[18] API Specification 6D, Specification for Pipeline Valves


[20] API Recommended Practice 13D, Rheology and Hydraulics of Oil-Well Drilling Fluids


[22] API Technical Report 10TR4, Selection of Centralizers for Primary Cementing Operations