

Recommended Practice for the Design of Solution-mined Underground Storage Facilities

API RECOMMENDED PRACTICE 1114
SECOND EDITION, JANUARY 2013



AMERICAN PETROLEUM INSTITUTE

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Downstream Segment

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Recommended Practice for the Design of Solution-mined Underground Storage Facilities

1 Scope

This recommended practice (RP) provides basic guidance on the design and development of new solution-mined underground storage facilities. It is based on the accumulated knowledge and experience of geologists, engineers, and other personnel in the petroleum industry. Users of this guide are reminded that no publication of this type can be complete nor can any written document be substituted for qualified, site-specific engineering analysis.

All aspects of solution-mined underground storage are covered, including selecting an appropriate site, physically developing the cavern, and testing and commissioning the cavern. Additionally, a section on plug and abandonment practices is included.

This RP does not apply to caverns used for natural gas storage, waste disposal purposes, caverns which are mechanically mined, depleted petroleum reserve cavities, or other underground storage systems which are not solution-mined.

See [API 1115](#) for guidance in the operation of solution-mined underground storage facilities.

2 Normative References

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

[API Recommended Practice 5A3](#), *Recommended Practice on Thread Compounds for Casing, Tubing, and Line Pipe*

[API Recommended Practice 5C1](#), *Recommended Practice for Care and Use of Casing and Tubing*

API Bulletin 5C3, *Bulletin on Formulas and Calculations for Casing, Tubing, Drill Pipe, and Line Pipe Properties*

[API Specification 6A](#), *Specification for Wellhead and Christmas Tree Equipment*

[API Standard 1104](#), *Welding of Pipelines and Related Facilities*

[API Recommended Practice 1115](#), *Recommended Practice on the Operation of Solution-Mined Underground Storage Facilities*

ASME¹, *Boiler and Pressure Vessel Code*, Section IX, "Welding and Brazing Qualifications"

3 Terms and Definitions

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

3.1

blanketing material

A fluid less dense than water and incapable of dissolving salt.

NOTE This is usually a light hydrocarbon liquid injected as a protective barrier between the solution-mining brine and casing-salt interface is usually used to control cavern development.

¹ ASME International, 3 Park Avenue, New York, New York 10016-5990, www.asme.org.

3.2**brine**

A saltwater solution said to be saturated when the maximum salt per unit weight has been dissolved [approximately 26 % by weight at 68 °F (20 °C)].

3.3**caprock**

A mantle composed chiefly of anhydrite, gypsum, and limestone.

3.4**casing seat**

A cement base formed at the bottom of the casing, providing both an anchor and pressure containment barrier.

3.5**casing, conductor**

The pipe placed within the drilled hole intended to protect the shallow water sands against contamination and to protect the drill site from sloughing-in during shallow drilling operations.

NOTE Line pipe is typically used for this large outside diameter pipe string.

3.6**casing, intermediate**

The casing placed in the top of competent salt that covers all lost circulation zones to ensure complete cementing on the production casing.

3.7**casing, production**

The principal casing forming the annulus through which stored products pass. Its diameter should be large enough to accommodate hanging of solution-mining and brine strings.

3.8**casing, surface**

Casing that is set to a depth below potable water strata and cemented to the surface to protect all potable water sands against contamination and the borehole against lost circulation.

3.9**cavern storage**

An underground cavity developed either by solution mining (leaching) of a salt formation or by conventional excavation for the purposes of storing liquid or gaseous products.

3.10**christmas tree**

An assembly of valves, actuators, sensors, chokes, pressure gauges, and spools installed on top of the wellhead to control flow into and out of the tubing and tubing-casing annulus.

3.11**circulation, direct**

The flow during solution mining in which fresh water is introduced into the salt formation through the center string with the brine then returned through the casing or string annulus.

NOTE This is the opposite of reverse circulation.

3.12**circulation, reverse**

The flow during solution mining in which fresh water is introduced into the salt formation through the casing or string annulus, with the brine then returned through the center string.

NOTE This is the opposite of direct circulation.

3.13**collapse pressure**

Pressure that, when applied to the exterior of a pipe or vessel, causes the pipe or vessel to collapse.

3.14**competency**

A term applicable to geological formations indicating a relative degree of mechanical and structural integrity.

3.15**convergence**

The time-dependent decrease of cavern storage volume due to creep. It is also dependent upon the internal cavity pressure.

3.16**creep**

The geological process that causes salt and other evaporatives to flow into subsurface voids that are operated at a significantly lower pressure than the pressure exerted on the walls of the cavity by the formation.

3.17**dispersant**

A material used to lower the consistency of cement to allow turbulent flow at lower pumping rates and to reduce pumping pressure.

NOTE Common dispersants include alkyl aryl sulfonate, polyphosphate, lignosulfonate, and certain organic acids.

3.18**effluent**

The brine formed during the solution-mining process that may carry along an amount of insoluble material for surface disposal.

3.19**gradient, operating**

The pressure gradient [pounds per square inch (psi) at the casing seat per foot of overburden] existing during cavern operation and is a function of the mode of operation (brine, product injection, or withdrawal), the rate of fluid injection or withdrawal and its relative density, and the tubing or casing string sizes.

3.20**gradient, pressure**

A parameter expressed as the ratio of pressure per unit depth (usually pounds per square inch per foot) and is used to determine the stress limitations of an underground formation.

3.21**solution mining**

The process of dissolving a solid material, generally for the purpose of forming a void or cavity.

NOTE An example is the creation of underground storage in a salt formation through fresh-water injection and brine removal.

3.22**lenticular**

Lens-shaped.

3.23**lithology**

The study or characterization of rock formations.

3.24**log**

A graphic representation of a subsurface feature obtained through any of several techniques (for example, gamma-ray absorption or sonar).

NOTE Typical applications are density logs for locating cavern tops or casing setting depths; sonar logs for internal cavern configurations; and interface logs that, when plotted against metered volume, can provide a guide for determining product volume.

3.25**mud**

The material used to facilitate the drilling process through cooling and lubricating action, removing cuttings from the hole, controlling subsurface pressures, cleaning the bottom of the hole, and releasing cuttings at the surface.

3.26**overburden**

The strata lying above the salt formations, generally sedimentary in character and composed of sands, shales, limestones, chalk, and anhydrites.

NOTE The depth of the overburden may vary from a few feet to several hundred feet.

3.27**piercement**

A descriptive term applied to salt domes that have pierced subsurface formations.

3.28**pillar**

A descriptive term applied to the residual structural salt that acts as both separating wall and roof support in adjacent, communicating cavern spaces.

3.29**pozzolan**

A cement additive of siliceous or aluminous material, including fly ash, used to provide increased resistance to sea water, sulfate bearing soils, reactive aggregate, or natural acid waters.

NOTE Substituting pozzolan materials for equal weights of cement increases the relative bulk of fine material, thereby improving workability and reducing bleeding and segregation.

3.30**porosity**

The ratio of the aggregate volume of interstices in a rock or soil to its total volume, or the percentage of void space in the formation.

3.31**product**

Refers to material stored in a cavern, usually a liquid or gaseous hydrocarbon.

3.32**product string**

An uncemented string hung inside the production casing, concentric with and outside of the brine string which allows product production or injection without allowing the flow to contact the production casing.

NOTE 1 This is also known as blanket string.

NOTE 2 This string is useful in cases where severe corrosion might occur or where it is desirable to be able to remove the casing for inspection along with the brine string.

3.33

rheology

The science of dealing with the deformation and flow of matter.

3.34

salt, bedded

A type of salt basin resulting from compressive tectonic forces (halotectonism).

3.35

salt, domal

A type of salt plug resulting from autonomous, isostatic salt movement (halokinesis).

3.36

seal-pad material

Synonymous with blanketing material (see 3.1).

3.37

sonar caliper

A device using acoustical wave reflection technology to ascertain the internal configuration of an underground space.

3.38

spool

A general term applied to a short pipe section that is flanged at both ends and used to couple other functional piping elements.

3.39

stope

Steplike excavations or formations relating to cavern geometry.

3.40

string

A general term applied to piping or casing suspended from the wellhead. The centermost string extends close to the cavern bottom and is used for brine injection and removal in operational caverns.

3.41

tubing (brine) string

The last string of pipe or casing placed in the well and is run inside the production casing to near the bottom of the cavity.

NOTE 1 Tubing is designed to be retrieved from the well and differs from other tubular strings that are normally cemented in place.

NOTE 2 Tubing that meets API standards normally ranges up to 4¹/₂ in.; however, for high-rate application, substantially larger pipe sizes may be required. In these instances, casing that meets API standards may be used as tubing.

NOTE 3 Nomenclature “tubing string,” “displacement string,” “brine string,” and “displacement string” are used synonymously in this document.

3.42

web

The in-situ mass separating adjacent underground caverns and is subject to pressure differentials resulting from varying modes of cavern operation.

3.43**well**

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

3.44**wellhead**

The ground-level surface equipment used to maintain control of the well, including the connecting casing heads, tubing head, and christmas tree.

4 Overview of Underground Storage

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.

5 Applicable Rules and Regulations

The creation or operation of solution-mined underground storage facilities is often regulated by federal, state, or local codes, regulations, ordinances, or rules. A review of the applicable rules and regulations is required prior to or in the initial stages of design of a solution-mined underground storage facility.

6 Salt Storage Overview

6.1 General

A solution-mined salt cavern for commodity storage is created through the planned solutioning of a naturally occurring bedded or domal salt formation. Solution mining simply requires exposing the salt formation by drilling a well, circulating fresh or low-salinity water in the well, and withdrawing the brine from the cavern. The salt in the formation dissolves, enlarging the well bore to form an even larger cavern.

The shape of the cavity depends on the solutioning procedure employed. The typical storage cavern resembles a cylinder, with the height several times greater than the diameter. The relatively small roof area enhances the probability of effective product recovery and minimizes the probability of the roof collapsing during service.

Concentric tubing strings are generally used to move stored product in and out of the cavern. A large U-tube is created for the flow, and because of the differences in densities between the product stored and the brine, a manometer effect is created. A simplified salt-dome storage cavity is illustrated in Figure 1.

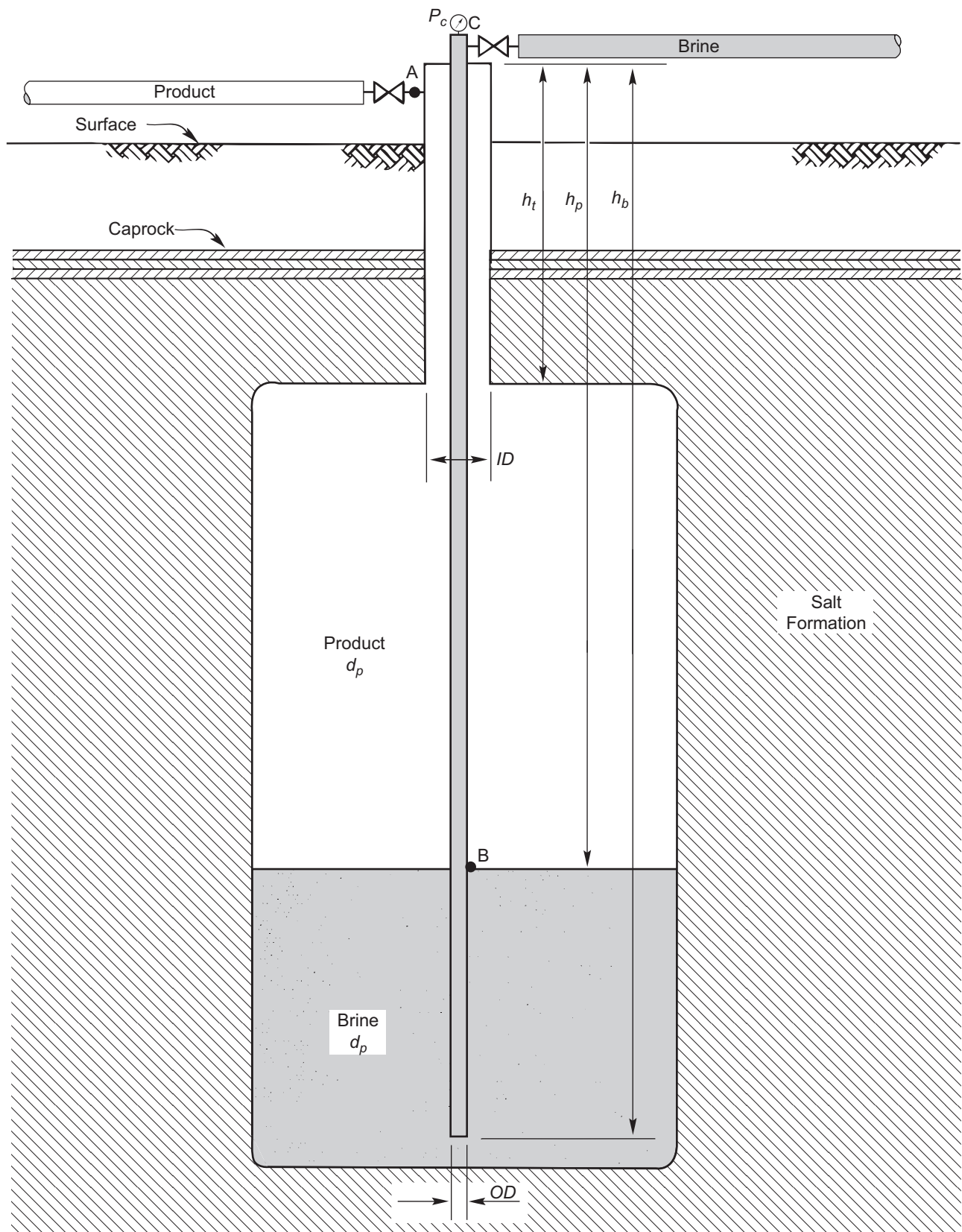


Figure 1—Simplified Salt Dome Storage Cavity Schematic

Injecting product is accomplished when the product is supplied to the wellhead at sufficient pressure to allow movement down the production casing and tubing annulus into the top of the cavity. This forces a corresponding movement of brine or water out of the cavity up the brine tubing string.

Product is withdrawn by reversing the injection process. In this case, brine is pumped into the cavity, forcing a corresponding movement of product out of the cavity up the tubing casing annulus.

Dry caverns do not use a displacement fluid and instead rely on downhole pumps to deliver product from the cavern. Dry caverns may be appropriate where high-ingress but low-egress flow rates are required.

6.2 Components

6.2.1 Tubing Strings

The common tubing string configuration includes a single tubing string (brine string) concentrically suspended within the production casing or a combination of a tubing string and a blanket string concentrically suspended in the production casing. The blanket string should be considered if high corrosion rates are expected or if it is desirable to pull and inspect the casing at a later date. The production casing, tubing, and blanket casing (if so equipped) shall be designed to accommodate the required flow rates, cavern pressure limitations, and surface equipment capability.

6.2.2 Wellhead Equipment

The wellhead equipment must be designed to properly contain, direct, and isolate the flow of stored product and displacement fluid into and out of the storage cavity. The wellhead equipment must be capable of withstanding the maximum possible product pressure on both the brine and product sides to provide protection against overfilling or tubing failure. Wellhead pressure sensing equipment must be provided that will aid in detecting leaks in the brine string, leaks in surface product or brine lines, or overfilling with product.

Shut-in valves capable of being remotely actuated should be provided on the wellhead. For some possible failures, these actuated valves should be automatically controlled (for example, in the event of low or high pressures, outside the safe operating range, in either the surface product or brine lines).

Another consideration in the wellhead design is the production casing pack-off (or secondary) seal. This seal is exposed to high-pressure product for the life of the well. Consider making this a highly reliable seal such as an elastomer with adequate extrusion control devices. If a blanket string is installed, it is usually hung in a mandrel much like the brine string.

6.2.3 Surface Facilities

6.2.3.1 General

Surface facilities to be considered for solution-mined cavity storage projects may include brine and fresh water systems; flare systems; product piping; injection pumps; compressors; product dryers and related equipment; pipelines and pipeline meter stations; and general support facilities such as control buildings, roads, and fire protection.

6.2.3.2 Brine and Fresh-water Systems

The brine system may require each of the following elements.

- a) A brine sourcing or producing facility, such as a dedicated source well or storage cavity under development.
- b) A brine storage facility, such as a surface brine pit.

- c) A brine distribution facility, with brine pump or pumps to provide the pressure necessary for product displacement and a degassing facility.
- d) A fresh-water flushing system to periodically dissolve incrustated salt in the brine tubing strings and return lines.
- e) A brine disposal facility to accommodate the excess brine normally generated from storage operations. Disposal could involve the sale of brine, injection into approved subsurface strata, or approved disposal at sea.

6.2.3.3 Flare Systems

A properly designed flare system shall be provided to burn or contain the flammable gases that may be released from the brine system. The flare system should also be designed to handle the volume of gas that will have to be vented in all emergency shut-in situations. This will include the flare rates that will occur between the time a wellhead shut-in occurs and the product fill system can be shut down, and the flare rates that will occur between the time a tubing overpressure is sensed and the wellhead can be shut-in.

6.2.3.4 Product Piping and Related Equipment

All product piping and related equipment shall be designed, installed, and operated in accordance with appropriate industry codes and/or government regulations.

7 Design Parameters

7.1 General

Salt storage caverns can be used for hydrocarbon storage when a suitable salt formation is conveniently located, when the volume of storage required is sufficiently large, when the product to be stored is compatible with the salt, and when the hydraulic requirements can be economically satisfied. The project life must be identified in the project definition stage.

7.2 Available Salt Formations

The first requirement is a suitable salt formation at an acceptable depth at the required location. Maps showing locations of suitable domal and basin salt formations are available through geological data sources.

7.3 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.

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.

7.4 Storage Volume Required

7.4.1 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. Special considerations inherent in the design of a salt storage cavern are discussed in 7.4.2 through 7.4.6.

7.4.2 Displacement-fluid Handling Facilities

Except for dry caverns, salt caverns require displacement-fluid handling facilities. The capacity of the cavern itself must be matched with a combination of brine storage, a brine disposal system, and a brine sourcing system.

7.4.3 Compressible Fluids

Storage cavern capacity normally is stated on a volumetric basis, such as barrels. However, 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.

7.4.4 Intentional Operational Solution-mining

Cavity capacity can be deliberately solution mined while operating as a storage facility. One such method would be to initially solution mine a cavity 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 cavity configuration is achieved. Both methods require carefully designed and controlled solution-mining programs to produce the desired cavern geometry.

7.4.5 Traps (Attics)

Care must be taken during solution mining to avoid the creation of traps (or cavity space) above the final product production casing string. During storage operations, such space will fill with product, which cannot be recovered. An insoluble hydrocarbon blanketing material should be used during the solution-mining phase to minimize attic creation. Provision should be made to monitor the level of the blanketing material during the solution-mining phase.

7.4.6 Cavern Dynamics

Cavern size will change over time due to two opposing processes: creep closure and operational solution mining. As discussed in Section 9, 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.

7.5 Displacement-fluid Characteristics

7.5.1 Saturation

Except in dry caverns, 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.