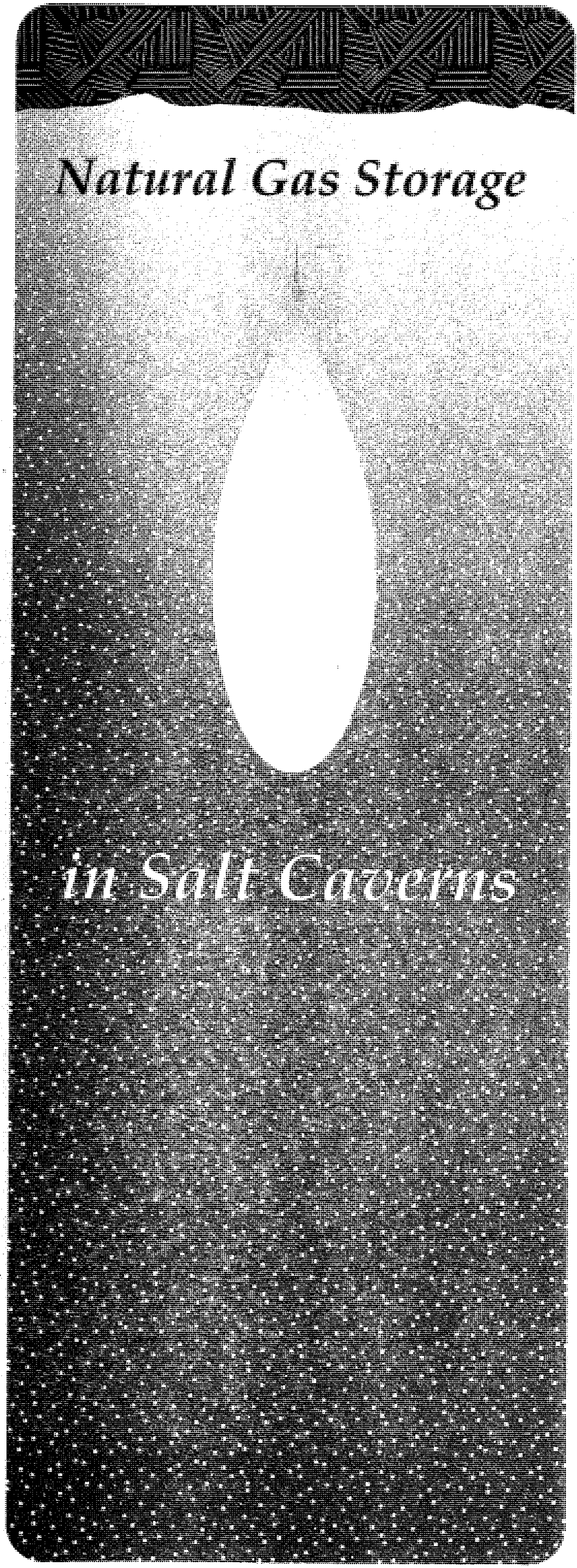


# A Guide for State Regulators

INTERSTATE OIL AND GAS COMPACT COMMISSION
DEDICATED TO THE CONSERVATION OF OIL AND GAS
★ 1935 ★

Prepared by the Energy Resources Committee
of the IOGCC

# NATURAL GAS STORAGE IN SALT CAVERNS

## *A GUIDE FOR STATE REGULATORS*

Since its publication in 1995, the Interstate Oil and Gas Compact Commission's (IOGCC) *Natural Gas Storage in Salt Caverns* has been widely acclaimed for its comprehensive research and reporting of guidelines addressing operational and safety issues associated with storing natural gas in underground salt caverns.

The National Association of Regulatory Utility Commissioners resolved in 1995 that the IOGCC report was "a model guideline for use by state regulatory agencies involved in the construction, operation, and safety of those portions of underground salt cavern storage facilities not covered by Federal pipeline safety regulations."

The U.S. Department of Transportation's Office of Pipeline Safety (OPS) also recognizes the value of a document for safety regulation of underground natural gas storage in salt caverns as well as the importance of each state's particular geology and circumstances when dealing with storage requirements. Consequently, OPS "encourages states that have underground salt cavern storage of natural gas subject to state authority to adopt the requirements in the IOGCC Guide, if such regulations are needed."

With these and several other endorsements, the IOGCC has depleted it original stock of reports. After discussion with the authors of the guide, it has been decided to reprint *Natural Gas Storage in Salt Caverns*. The information in the guide is the same as the original report, but updates have been made to the state contact list. (Appendix C)

As chairman of the IOGCC Energy Resources, Research and Technology Committee, I know this guide will continue to assist states in the development of regulatory programs for salt cavern storage of natural gas.

Theodore Streit
Chief/Commissioner
West Virginia Division of Environmental Protection, Office of Oil and Gas
Chairman, Energy Resources, Research and Technology Committee

Prepared by the Energy Resources Committee of the
Interstate Oil and Gas Compact Commission
Reprinted February 1998

# *CONTENTS*

## *FIGURES*

## *FOREWORD*

As chairman of the Energy Resources Committee of the Interstate Oil and Gas Compact Commission, I am very pleased to present the result of the committee's work to develop guidelines for the regulation of natural gas storage in salt caverns. The guidelines in this document have been developed and refined through the participation of IOGCC member states, industry trade associations, salt cavern storage operators, and other interested parties. Where possible, every effort has been made to reach consensus among the different interests.

In an earlier study, the IOGCC identified greater use of market hubs and storage as key in promoting growth in gas sales. Salt cavern storage benefits all segments of our industry, particularly when it is used as an "uncoupling mechanism" located at a market hub.

Salt storage facilities in the production area provide backup to flowing reserves. This increased reliability allows producers to enjoy base load pricing for intermittent production. Producers can boost their returns by moving gas at maximum rates, insulated from short-term demand fluctuations. At pipeline intersections, these facilities serve as warehouses to assist operators in balancing load. Balanced flow contributes to full resource utilization, which is essential as the pipelines compete to provide reliable service at the lowest cost. In the market area, salt cavern storage allows local distributors of natural gas to reliably serve short-term demand peaks with a minimum of year-round transportation.

If operated in an open and coordinated manner throughout the nation, market centers or hubs will ensure that producer gas flows to the consumers who offer the highest price through the lowest-cost transportation. Markets will enjoy open access to the lowest-cost bundled gas service. Natural gas storage in salt caverns contributes to achieving these benefits.

The U.S. natural gas storage industry has a remarkable safety record to date. However, there are undeniable risks associated with handling large quantities of flammable materials at high pressure, and uncertainties in the exploration of unseen geology. We minimize these risks by adhering to clearly expressed technical guidelines and conservative operating procedures which provide sufficient protection when they are employed in a careful and reasoned manner.

High-cycle operation of salt caverns filled with natural gas is a relatively novel technique in the United States, although seasonal cycling was practiced at a few locations prior to deregulation. It is not surprising that most states have not given this technique regulatory attention. However, since FERC Order 636 was published in 1992, nearly 100 new storage projects have been proposed. About 40 percent of these involve salt caverns. The potential dangers associated with this sort of facility include fires or explosions, subsidence, loss of product, and contamination of surrounding storage, the environment, or communities. There are techniques for measuring these risks and for mitigating or eliminating harm.

Because most states have not yet established regulations for salt cavern storage of natural gas, and because accidents have occurred in other types of hydrocarbon storage facilities, it has been suggested that federal regulations may be needed in this area.

From a technical standpoint, a uniform federal regulation is not sound because geology and potential risks vary widely from state to state. Similarly, the potential rewards of gas storage do not fall evenly on all states. More fundamentally, we believe that balancing reward with risk in state resource development should remain solely a matter of state policy. If the states move to proactively regulate salt cavern storage of natural gas, risks can be minimized and federal regulations may be avoided.

IOGCC recognized an opportunity to serve its membership by gathering existing regulations for natural gas storage in salt caverns. These materials were distributed at our meeting in December 1994. At that time we formed a subcommittee to:

- more clearly identify the rewards and risks involved in this area
- propose performance guidelines
- identify regulatory issues
- identify associated regulatory references

Our subcommittee is composed of federal and state regulators as well as professionals from many of our finest industry associations. The ideas, input and comments provided by all of the interested organizations and individuals were invaluable for the creation of this document. On behalf of the IOGCC, I want to thank all of those individuals who assisted with this project. I personally wish to thank our subcommittee co-chairs, Buster Heneman and John King, whose efforts made this report a reality.

James A. Slutz
Chairman, Energy Resources Committee
Interstate Oil and Gas Compact Commission

## *Interstate Oil and Gas Compact Commission*

**Member States**

Alabama, Alaska, Arizona, Arkansas, California, Colorado, Illinois, Indiana, Kansas, Kentucky, Louisiana, Maryland, Michigan, Mississippi, Montana, Nebraska, Nevada, New Mexico, New York, North Dakota, Ohio, Oklahoma, Pennsylvania, South Dakota, Texas, Utah, Virginia, West Virginia, Wyoming

**Associates**

Georgia, Idaho, North Carolina, Oregon, South Carolina, Washington

## *ACKNOWLEDGMENTS*

The definitions and requirements sections of these guidelines were adapted, with permission, from *Storage of Hydrocarbons in Underground Formations* (CSA Standard Z341-93) published and copyrighted by the Canadian Standards Association, 178 Rexdale Blvd., Rexdale, Ontario, Canada, M9W 1R3. We appreciate the cooperation of the CSA in allowing us to use this material. However, the CSA is not responsible for the way in which the information is presented, nor for the interpretation of the material. Readers interested in Canadian regulations should contact the CSA because the material contained here may not reflect updates and amendments to Canadian regulations.

We would like to thank the following members of the Natural Gas Storage subcommittee of the IOGCC Energy Resources Committee for their suggestions and review of the guidelines and definitions sections: James Slutz, Indiana Department of Natural Resources; John Erickson, vice-president, Operating and Engineering Services, American Gas Association; Donna Bobbish, director, Gas Policy Office, U.S. Department of Energy; J. Michael Biddison, Public Utilities Commission of Ohio; Mary McDaniel, manager of pipeline safety, and Richard Ginn, assistant director for UIC, Railroad Commission of Texas; John Paul Johnson, director of industrial relations, Natural Gas Supply Association; Cesar De Leon, deputy associate administrator, Office of Pipeline Safety, U.S. Department of Transportation; and Stephen E. Foh, principal technology manager, storage research, Gas Research Institute.

In addition to these subcommittee members, the following individuals made valuable contributions in preparing these guidelines: Robert Thoms, AGM, Inc.; Michel Dussaud, Sofregas US, Inc.; James Todd and James Linn, Sandia National Laboratories; Bob Jones and Ruth Haas, Tech Reps., Inc.; and Jack W. Gatewood, Tejas Power Corp.

Helmuth J. Heneman
John T. King

Co-chairs, Natural Gas Storage Subcommittee

## *DEFINITIONS*

The following definitions are used in this guide:

**Abandoned well**--a well whose use has been permanently discontinued and that has been plugged.

**Annulus**--the space between two casings, between a casing and the tubing, or between the casing and the adjacent formations.

**Base gas**--the volume of gas required as permanent storage inventory to maintain adequate cavity pressure for meeting minimum gas deliverability demands throughout the withdrawal period (also called "cushion gas" or pad gas).

**Base pressure**--the lower limit of gas storage pressure below which gas is seldom produced and only base gas remains.

**Bedded salt**--a layered salt deposit.

**Blanket material**--Material used in solution mining to prevent erosion of the cavern roof or deterioration of salt around the casing seat. Blanket materials must be lighter than water and inert to salt. They are generally hydrocarbons such as diesel oil, condensate or liquified petroleum products.

**Blowout**--the uncontrolled flow of oil, gas, and/or water from a geological formation that a drilled hole has penetrated.

**Blowout preventer**--a stack or assembly of valves attached to the top of the casing during drilling or workover operations to control well pressure.

**Bottomhole**--the lowermost portion of the well.

**Brine**--saline water naturally occurring in porous sedimentary rock formations; fluid resulting from the dissolution of salt formations with fresh water for salt solution mining.

**Brine well**--a well used for dissolving salt from a salt formation, adding brine to, or taking brine from a salt cavern.

**Brining**--the process of dissolving salt formations using fresh water pumped and circulated into and through wells for salt solution mining.

**Caprock**--a formation consisting mainly of anhydrite, gypsum, and sometimes calcite that frequently overlies domal salt.

**Casing**--metallic or nonmetallic pipe placed in the borehole to support the sides of the bore and to prevent subsurface migration of fluids out of or into the borehole.

**Surface casing**--a pipe, usually metallic, placed in the borehole and cemented into place to control a well and protect underground sources of drinking water (USDW) from damage during drilling, mining, or production operations.

**Intermediate casing**--a pipe, usually metallic, placed in the borehole inside the surface casing and cemented in place. The length of the intermediate casing is such that it extends beyond surface casing and serves to seal off any fluid-bearing zones, secondary production zones, or noncompetent rock formations prior to drilling into the storage zone.

**Production casing**--a pipe, usually metallic, placed in the borehole and cemented into place inside the surface or intermediate casing. The length of the production casing is such that it ends at, or into, the salt formation used for storage.

**Casing inspection log**--a log or combination of logs which provides an indication of:
(a) the depth of penetration of anomalies into the well casing;
(b) external and internal corrosion; and
(c) pits, perforations, metal loss, and metal thickness.

**Casing seat**--the final sealed position of casing within the formation, usually assumed at the casing shoe.

**Casing shoe**--a reinforcing collar of steel welded or screwed onto the bottom joint of casing to prevent abrasion or distortion of the casing as it is run into the bore hole.

**Cathodic protection**--an electrochemical technique for protecting metal structures such as well casings, pipelines, tanks, and buildings in which electric currents are induced to offset the current associated with metal corrosion.

**Cementing**--the operation in which a cement slurry is pumped and circulated down a well through the inside of the casing and then upward into the annular space behind the casing to (1) firmly fix the casing in the hole; (2) buttress the casing string against formation, production, or injection pressures; (3) protect the casing from corrosion caused by exposure to formation fluids; and (4) provide a seal against flow of fluids in the annular space.

**Cement integrity log**--a downhole geophysical evaluation survey used to indicate the quality and quantity of cement bonding between casing and rock formations.

**Communication**--the passage of gas or water (fluid) through porous and permeable connections from one cavern to another in a single formation, from formation to formation, or from any formation to any ground water aquifer or to the surface.

**Containment**--the ability of the storage cavern to resist leakage or migration of the fluids contained therein either through wellbores, caprock, or at the edges of the subsurface storage cavern.

**Convergence**--the time-dependent decrease of cavern storage volume as a result of salt creep due to the difference in formation stresses and the cavern pressure.

**Creep**--the time-dependent deformation of materials in response to deviatoric load.

**Depressurize**--the relieving of pressure from a cavern, vessel, or pipeline.

**Domal salt**--a type of salt plug resulting from autonomous, isostatic salt movement.

**Drawdown**--the lowering of inventory or pressure by withdrawal.

**Effluent**--the brine formed during the solution mining process which may carry along an amount of insoluble material for disposal.

**Flow rate**--the volume measure of the flow of a fluid per unit of time.

**Fluid**--any material or substance that flows or moves and that is in a semisolid, liquid, sludgelike, or gaseous state.

**Formation**--a body of rock characterized by a distinguishing lithology that forms an identifiable geological unit and is mappable on the earth's surface or traceable in the subsurface.

**Fracture gradient**--the pressure gradient which, if applied to subsurface formations, will cause the formations to physically fracture.

**Fresh-water strata**--porous and permeable, fresh-water-bearing rock formations.

**Gradient (operating)**--the pressure gradient (pressure at casing seat per foot of depth of overburden) existing during cavern operation. It is a function of the mode of operation (brine-gas injection-withdrawal), the rate of fluid injection or withdrawal and its relative density, and the tubing and casing string sizes.

**Gradient (pressure)**--the ratio of pressure per unit of depth.

**Hanging string**--a concentric inner production casing or tubing hung from the wellhead and normally used to inject and withdraw gases or displace fluid into and out of the cavern.

**Hydraulic fracturing**--a method of fracturing formations with fluid injected at high pressures; sometimes used to connect two wells drilled into salt formations.

**Injection well**--a well into which fluids other than the fluids associated with active drilling operations are being injected.

**Interface**--a surface that forms a common boundary between two separate and immiscible fluids in a cavern (e.g., between brine and the gas in storage).

**Isopach**--a contour line depicting areas of equal thickness of subsurface geological formations.

**Liner**--casing normally installed within production casing for remedial repairs.

**Lithology**--the description of physical characteristics of rock formations.

**Log**--a graphic representation of a subsurface feature obtained through any of several techniques (e.g., sonar or gamma ray absorption). Typical applications are density logs for locating cavern tops and/or setting casing depths, sonar logs for determining cavern shape and volume, and interface logs, which, when plotted against meter volume, can provide a guide for determining volume.

**Maximum anticipated differential pressure (MADP)**--the minimum principal stress of the salt formation, acting on the bottom of the plug, less the hydrostatic head of the wellbore fluid. If no other data are available, the minimum principal stress can be estimated by assuming a stress gradient of 1 psi/ft.

**Mechanical integrity test**--a procedure that verifies that a cavern or casing string is capable of containing fluids within design pressure limitations with no significant loss from the cavern or cavern well.

**Migration**--the underground movement of fluid resulting from a difference in pressure between the storage zone and an adjacent formation or cavern.

**Natural gas**--gaseous forms of hydrocarbons consisting primarily of methane.

**Neat cement**--cement that does not contain any extenders or density-reducing additives that affect its curing time and compressive strength.

**Overburden**--all formations and fluids overlying a storage zone.

**Permeability**--the degree of connectivity of the pore spaces within a rock which facilitates the movement of fluids through it; a measure of the rock's capacity to transmit fluids.

**Pillar**--a descriptive term applied to the residual structural salt acting as both separating wall and roof support in adjacent cavern spaces.

**Porosity**--the state or quality of being porous; the volume of the fluid-filled pore space within a formation expressed as a percentage of the total volume of the rock mass containing the pores.

**Rock**--any naturally formed aggregate of mineral matter, whether or not coherent, constituting an essential and appreciable part of the earth's crust.

**Rock salt**--halite; sodium chloride occurring as a crystalline, fibrous, or granular deposit.

**Salt cavern**--a cavern constructed within a soluble rock formation, commonly rock salt, by circulating fresh water in a controlled manner to create an underground storage chamber.

**Salt formation**--a rock formation composed of predominantly sodium chloride deposits which is generally impervious to liquid or gaseous hydrocarbons, has compressive strength comparable to that of concrete, moves plastically to seal fractures or voids, and can be easily mined by dissolution with water.

**Snubbing unit**--a portable assembly that allows tubing to be removed from or inserted into a well under high pressure.

**Solution mining**--the process of injecting fluid into a well to dissolve rock salt or other readily soluble rock or mineral, and the production of the resultant brine.

**Sonar surveying**--use of acoustical wave reflection technology to ascertain the internal configuration of an underground space.

**Storage facility**--an operation storing compressed natural gas, in one or more salt caverns and including piping, surface equipment, structures, and the site area.

**Storage zone**--the zone contained within the vertical interval of a cavern and the lateral extent of formation directly affected by the storage operation.

**String**--a general term applied to piping or casing suspended from the wellhead. The inner string extends close to the cavern bottom and is used to inject and remove brine in operational caverns.

**Web**--the *in situ* mass separating adjacent underground caverns that is subject to pressure differentials resulting from varying modes of cavern operation.

**Well**--the cased hole created to provide access to an underground cavern.

**Wellhead**-- ground-level surface equipment consisting of a master valve or series of valves used to maintain control of the well.

**Wireline logging tool**--a device or instrument used to measure subsurface rock characteristics through electrical, acoustic, or radioactive methods; measurements are made in the well with the devices connected by a wire cable to monitoring equipment on the surface.

# *PART I OVERVIEW*

# *1 NATURAL GAS STORAGE IN SALT CAVERNS*

## 1.1 INTRODUCTION

While the Department of Transportation has jurisdiction over the design, construction, operation, and maintenance of natural gas transmission lines and distribution facilities, it does not have regulations addressing salt cavern storage facilities. There is no uniform standard or specific guidance to help state regulators develop standards. For states with little experience in this area and not much expertise available, drawing up such regulations is a daunting task. The guidelines in this document have been prepared as a way to help state regulators and industry address the operational and safety problems of storing natural gas in underground salt caverns.

Salt caverns make excellent low-cost storage containers for natural gas. The impermeable nature of salt structures ensures that the contents are retained. Salt caverns that can store large quantities of natural gas under high pressure can be developed at minimal cost. Hollow cavities allow an unimpeded flow of gas to and from storage. When carefully located and properly constructed, salt storage facilities can reduce the cost of moving gas reliably from wellhead to burner tip, and thereby increase the competitiveness of natural gas in the energy market.

In developing a cavern, salt is dissolved with water, and controlled solution mining or leaching is used to extract the salt from underground deposits. In this process, water is injected into a well to dissolve rock salt or other minerals and produce brine, which is then removed. Figure 1 shows this process. The most common technique used to develop storage caverns, the single-well technique, uses a concentric arrangement of tubes to inject water and withdraw the brine from the same well. The multiwell technique, in which water is injected and brine is produced through different wells, is more common when a cavern is not initially intended for storage, when salt stock dimensions are limited, or very high leaching rates are needed. Cavern roofs are kept from dissolving by the injection of a blanket material (generally made of hydrocarbons) that is lighter than water and inert to salt. Diesel oil, condensates, and liquefied petroleum gas are common blanket materials.

## 1.2 BENEFITS OF SALT CAVERN STORAGE

As the gas industry reorganizes following FERC Order 636, salt cavern storage of natural gas has emerged as a highly desirable means to achieve the efficiencies envisioned by the order. Salt caverns that are properly located, constructed, and operated can help the natural gas industry become more cost competitive by reducing capital requirements and operating costs.

Where they are available, salt caverns are the least expensive mechanism for modulating gas flow on an intraweek (or even intraday) basis. The capital costs for the services provided by such facilities are lower because of the minimal need for base gas and compression equipment. Easy compression reduces operating costs as well.

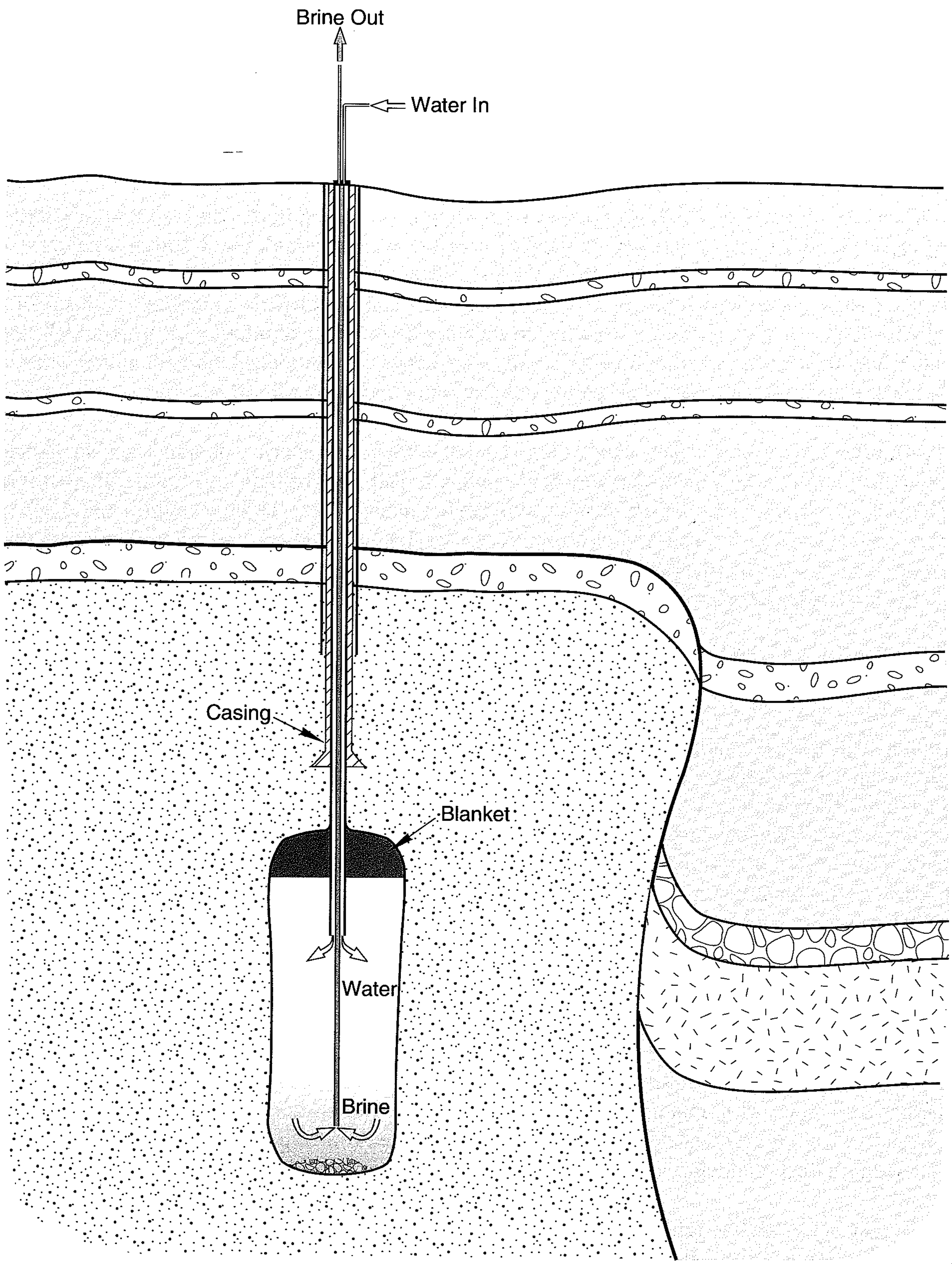


Figure 1. Representative gas storage cavern during leaching in domal salt.

When they are located in a production area, salt cavern facilities can boost the prices and returns at the wellhead in a number of ways. A small backup inventory in such a facility allows a producer to sell a higher proportion of his gas at premium prices because he can maintain a constant flow for his buyers. Space in a cavern can be used to store lower-priced weekend production so that it can be sold in weekday markets. Cavern storage also allows producers to sell at maximum flow rates to markets that require high reliability. The faster production of gas inventory enhances returns, as does the ability to temporarily take wells off production without losing markets or margins.

Salt caverns that are strategically positioned on long-haul natural gas pipelines can facilitate the balancing of loads and serve as cost-effective storage for line pack--the gas that has to be kept in the pipeline to maintain pressure and keep it operative. Salt caverns can act as a bellows, storing both gas and the energy necessary to build pressure in the pipeline. Caverns facilitate a nearly instantaneous balancing of receipts with deliveries. Since pipelines have a relatively high fixed-cost structure, fluctuations in either production or consumption can significantly affect the use of the pipeline and profits. On the other hand, with high levels of throughput, costs can be amortized with lower unit charges.

In market areas, salt cavern storage increases supply security for local gas distributors. It also reduces the need for transportation demand charges (i.e., reservation charges or standby fees charged by pipelines for access to their system), the likelihood of imbalance penalties, and the need to buy expensive swing service (i.e., the right to require a producer to modulate his production). Salt cavern storage can be effectively used to smooth weekly or daily demand curves, and to make deliveries in times of extreme need.

Finally, when the storage facilities are located at the intersection of many pipelines, they help create "market centers" that efficiently focus commercial transactions. In such centers, cavern storage assists in managing flow and supports a multitude of related services, such as "borrowing" gas for a short period, "parking" or temporarily storing it, and competitive shopping for prices. Integrated systems of such market centers may characterize the natural gas market of the future.

This future will depend to a large extent on how well salt caverns are constructed and how safely they are operated, and this will in turn depend on the guidelines adopted for regulation of storage. The next section discusses some of the components that are critical in storing natural gas in salt caverns.

## 1.3 Critical Components of Gas Storage in Salt Caverns

### Salt Barrier

A salt cavern can be developed specifically to store natural gas, or an existing cavern developed for brine production or to store liquid products can be converted for natural gas storage. When a salt cavern is used to store natural gas, the gas is held under pressure. Pressure increases as additional gas is stored in the cavern and decreases as the gas is withdrawn. This pressurization-expansion process requires that a range of operating pressures be defined. The maximum operating pressure, generally defined at the bottom of the last cemented casing string, is the pressure that should not be exceeded when gas is injected into the cavern to avoid salt fracture and preserve the integrity of the well and the cavern. The minimum operating pressure is the pressure that must be maintained in the cavern at the end of withdrawal to keep it stable and minimize closure and surface subsidence. Figure 2 shows a schematic of an operating well.

Salt is tight and impervious as long as the maximum operating pressure is not exceeded. It provides a natural barrier to fluid migration out of the cavern. Natural gas can be held tightly in the cavern as long as the integrity of this barrier can be maintained. If this barrier is destroyed either through the solution mining process (salt is dissolved at the roof of the cavern up to the caprock, for instance), or as a result of a geomechanical accident (such as partial collapse of the roof of the cavern), then the integrity of the cavern may be seriously endangered. In certain conditions, especially in bedded salt formations, salt can be interbedded with porous or fractured rock layers. The risk of gas migration through these interbeds should be addressed carefully during the evaluation of the project.

Another cause of salt barrier loss is inadvertent communication between neighboring caverns or wells. This may result from the loss of control of the solution mining process in the cavern during its development, or during the mining or operation of any neighboring caverns. There may be undesirable shape development at the roof of the cavern if the blanket material is not properly controlled. This may also happen if seams of salt more soluble than the common sodium chloride salt are present in the formation. Communication with adjacent caverns may also occur through activity outside the cavern, especially when the storage cavern is located near other caverns that continue to enlarge by solutioning.

**Cavern Well**

The storage cavern communicates with the surface through a well, and sometimes through more than one well. The well is composed of a wellhead and strings of casings cemented to the surrounding rock. It may also be completed with tubular strings set on hangers in the wellhead. At least one tubular string is required during the dewatering of the cavern. The cavern well and all components must also provide a barrier that is tight to gas and resilient to any inside or outside causes of deterioration through corrosion or geomechanical stress.

One of the most critical components of the cavern well is the cementation of the last casing string, especially around the casing shoe. An adequate bond must be achieved between casing and cement and between cement and rock over a height sufficient to ensure an effective seal for containment of fluids.

Another critical component of the cavern well is the dewatering tubular string hung in the wellhead. If this string is broken during dewatering of the cavern, by the fall of a salt ledge or slab, for example, this may result in sudden migration of natural gas to the surface and possibly the inability to dewater a significant portion of the cavern space available for storage.

**Geomechanical Stability**

A salt cavern, like any other underground opening, is subject to the stress in the formation surrounding the cavern. Its stability is affected by the cavern shape, the thickness of salt overlying the cavern, the distance between the storage cavern and neighboring caverns, and the distance

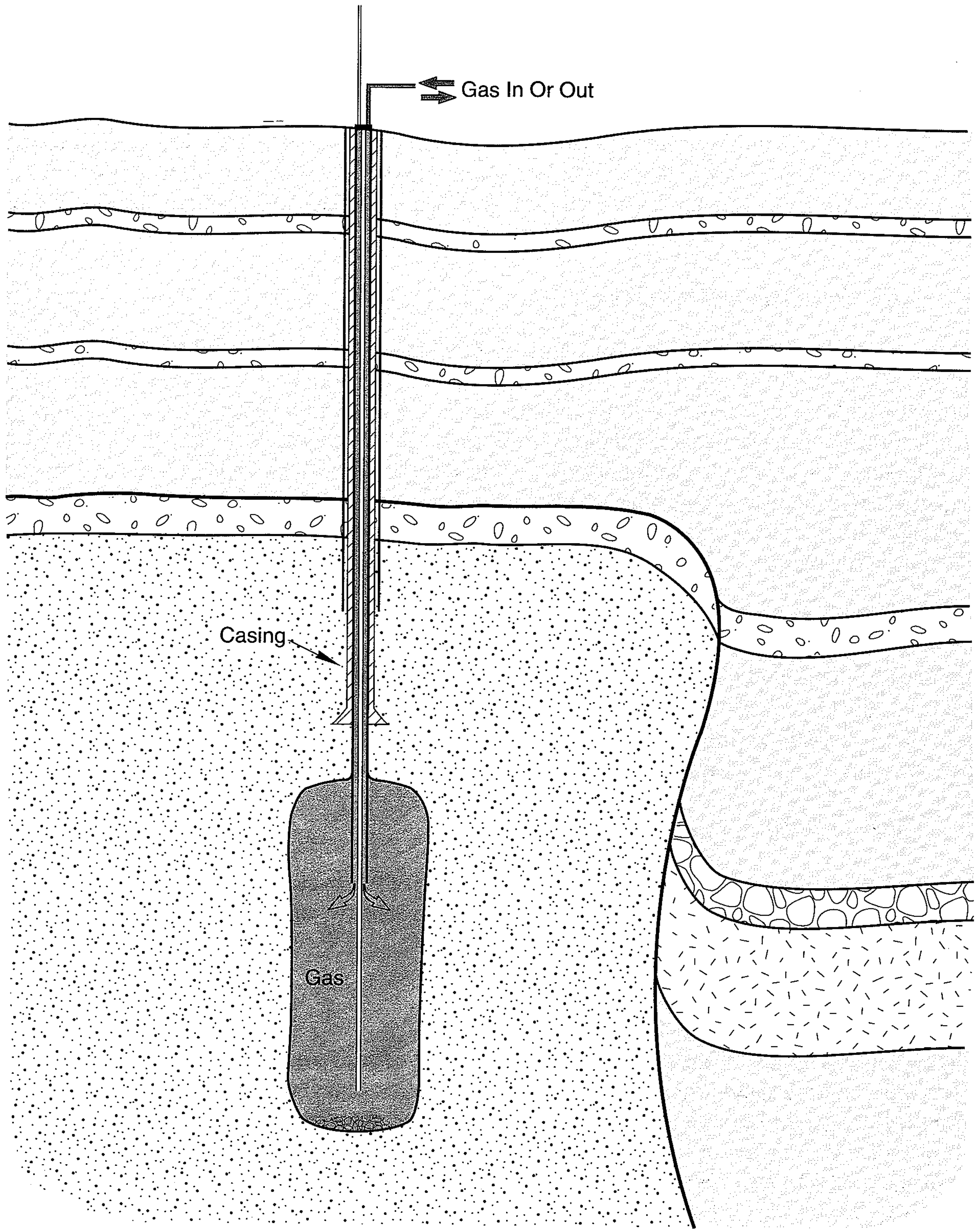


Figure 2. Representative gas storage cavern during operation.

between the cavern and the edge of the dome (in the case of domal salt). Prior to mining, the distribution of this stress mostly results from the weight of the overburden material from the surface to the depth where the cavern is planned. This is called the lithostatic pressure, and is generally close to 1 pound per square inch (psi) per foot of depth. It can be evaluated by downhole logging or by frac-testing (that is, pressurizing selected salt strata to initiate fractures). The local stress distribution can also be affected by the tectonics specific to the location, for instance, if the salt formation has been deformed by geologic movement, such as lateral thrusting. Since the stress distribution is modified by the construction of the cavern, several consequences should be considered in cavern design, depending on the geomechanical characteristics of the salt formation and its surroundings.

***Salt Creeping and Convergence***

Salt is a plastic viscoelastic material that creeps under stress. An advantage of this is that salt is a self-healing material: any fracture developed by exceeding the maximum operating pressure, for example, will close when the pressure is normal again. It has been proven that salt can stand large deformation by creeping without failing. Unfortunately, salt creep results in loss of volume or convergence of a cavern. The exact limit of the convergence is unknown and varies from cavern to cavern. All caverns will converge, and in most cases, without any detrimental consequences for their integrity. However, excessive convergence is to be avoided because valuable storage volume will be lost and cavern integrity may be threatened if repeated roof collapses occur.

***Roof Collapse***

The roof of the cavern is generally the cavern component that is most subject to tensile stress. Salt is usually quite resilient to compression, but not to tension. When a cavern is developed with an overly extended flat roof, tensile stress is concentrated above the cavern and the unsupported roof may collapse. The cavern's integrity may be seriously endangered.

***Web or Pillar Collapse***

Cavern stability also depends on the web or pillar of salt left between caverns. As in the "room-and-pillar" mining technique, if not enough pillar or web is left to support the suite of caverns, the web or pillars may collapse.

***Surface Subsidence***

Subsidence will usually occur at the surface as the result of convergence or collapse. If subsidence is too great and too rapid, it may affect the surface facilities, buildings, equipment, and piping. Generally, subsidence caused by salt creep and convergence is limited and slow. However, the collapse of a roof or cavern may result in sudden major subsidence at the surface and the formation of sinkholes around the cavern well. This could produce major destruction of surface equipment, and gas migration to the surface.

## 1.4 CONCLUSION: THE NEED FOR REGULATION

A review of the various critical components of gas storage in salt caverns reveals the need for regulating both the construction of new caverns and the conversion of existing caverns to gas storage, and their operation.

### Construction and Operation of New Caverns

Standards and regulatory guidelines must be established for the various stages of the construction and operation of a new cavern. First, at the planning stage, it is necessary to ensure that the design of the well for each cavern (if more than one is planned), and of the overall facility, meets the standards of the industry. This must be based on a geological review of the location that is sufficiently extended in depth and in area to cover all features capable of affecting the storage caverns and wells. In addition, the design of caverns and cavern wells must be based on a detailed knowledge of the geology of the location, obtained through running an adequate set of downhole logs and through coring salt and surrounding rocks to obtain representative samples. Finally, the geomechanical stability of the cavern(s) must be thoroughly addressed by appropriate geomechanical analysis techniques (usually two-dimensional or three-dimensional finite-element computer codes) supported by adequate geomechanical salt core data. Three-dimensional analysis may be needed when a cavern or its surroundings are not axisymmetric.

During construction of the cavern well and of the cavern, inspection and testing procedures should be followed in order to verify, first, the integrity of the cavern well after drilling and prior to solution mining, and second, the integrity of the cavern and final casing shoe after solution mining and before the cavern is filled with gas.

Finally, during the operation of the gas storage cavern, records of operations must be kept and turned over to the appropriate regulatory commission. Surface subsidence should be periodically measured and reported as well, unless it is proven that the subsidence rate is below some prenegotiated level. The cavern's integrity should also be periodically verified through approved testing procedures.

### Conversion of Existing Caverns to Gas Storage

The conversion of existing caverns to gas storage should meet the same design requirements as new cavern construction. If data are missing, they should be collected through additional investigative work such as drilling and testing cores or other approved methods. The cavern's integrity should be verified before it is filled with gas. During the operation of the storage cavern, the same standards and regulatory guidelines that apply to new caverns should be applied to converted caverns.

## 1.5 SCOPE OF THIS DOCUMENT

While the U.S. Department of Transportation has jurisdiction over the transmission and storage of natural gas, the responsibility for enforcing the safety of storage facilities has been left to the states. The Department of Transportation has provided neither standards nor specific guidance for the regulation of underground storage. Many states have little experience in the area of gas storage in salt caverns.

The guidelines in this document are based on industry practices, existing state rules, and on regulations developed by the Canadian Standards Association. They cover the minimum design, construction, operation, abandonment, and safety aspects of storing natural gas in domal and bedded salt formations, and the associated equipment. This equipment includes all subsurface process equipment, the wellhead, and all safety equipment related to storage facilities, wells, and wellheads. The guidelines do not apply to:

- underground storage facilities for gases other than natural gas
- underground storage of natural gas in structures other than solution-mined salt caverns, i.e., conventional mines, natural gas reservoirs, aquifers, or reef formations
- design and fabrication of pressure vessels that are covered by pressure vessel codes
- heat exchangers, pumps, compressors, and piping in processing plant facilities, manufacturing plants, or industrial plants that are covered by appropriate codes
- gathering lines, flow line meters, compressors, and associated surface equipment beyond the first emergency shutdown or blocking valve

It is not the intent of these guidelines to prevent the development of new equipment or practices, or to prescribe how such innovations should be handled.

## 1.6 Existing Regulations

Where any requirements of these guidelines are at variance with the requirements of existing standards or codes, the requirements of those standards should govern. This statement should be noted in particular for those items regulated by the *Code of Federal Regulations* (CFR), Part 192. These guidelines should govern the construction, operation, safety, and abandonment of storage facilities only insofar as the requirements are incorporated into regulations promulgated by state agencies responsible for overseeing natural gas storage. In most cases, the storage cavern and the wellhead up to the outlet of the "wing valve" should be regulated by the state (see Figure 3). Department of Transportation rules apply to the pipe, valves, and other appurtenances attached to pipes, compressor units, metering stations, regulator stations, holders, and fabricated assemblies at the surface beyond the wing valve.

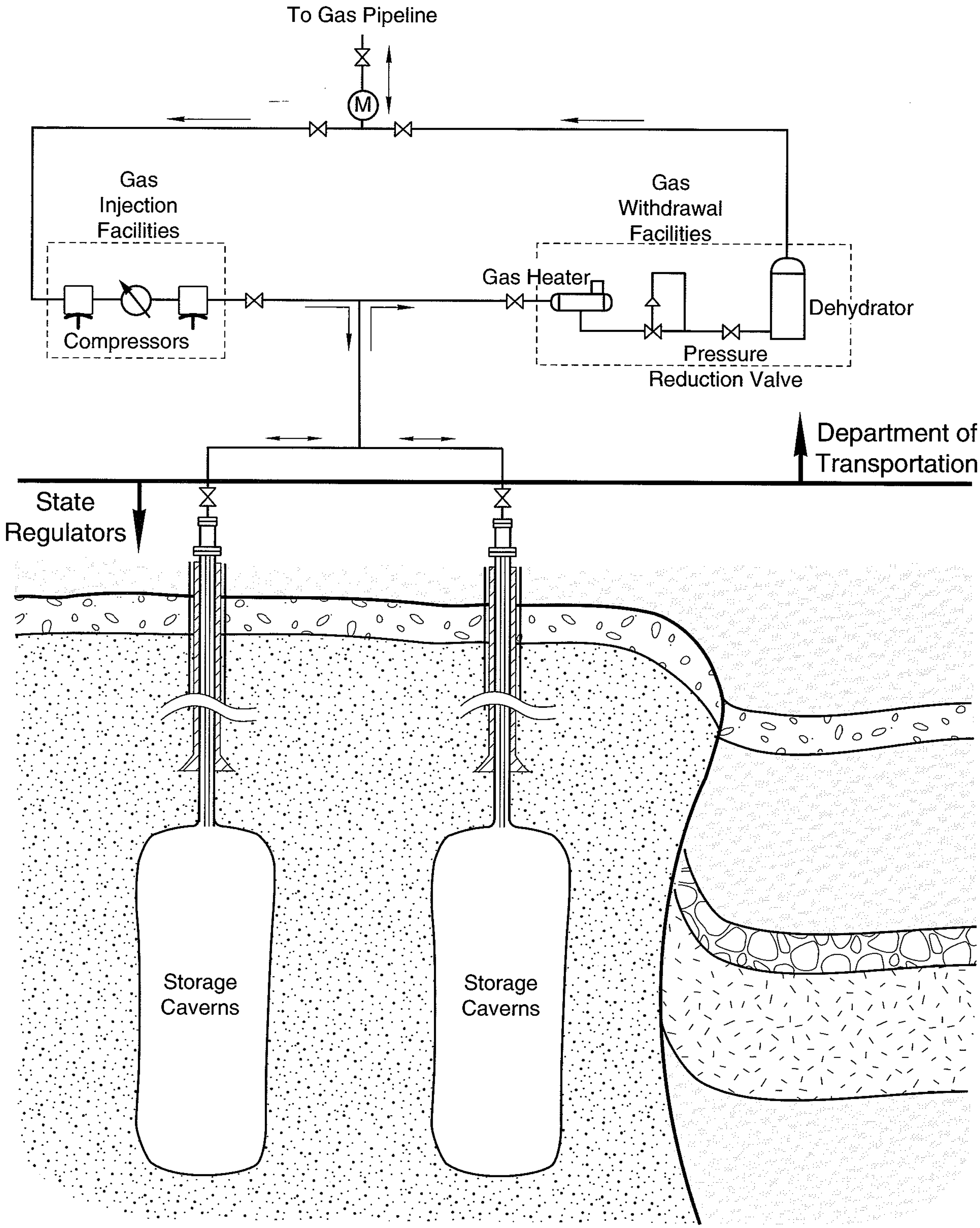


Figure 3. Breakdown of areas of state and federal regulations of natural gas production.

# *PART II GUIDELINES*

# 2 *LOCATION OF SALT CAVERNS*

## 2.1 General

Both technical and public requirements should be considered in locating storage caverns and related surface facilities. Technical considerations include geology, topography, maintenance, and effects on other subsurface activities. Public considerations include monitoring and emergency response requirements relative to surface and near-surface use by the general populace near storage facilities.

## 2.2 Site Selection Criteria

Storage facilities should be designed to minimize effects on the surface and subsurface. During site selection, consideration should be given to the following factors:
(a) proximity to populated areas and public rights-of-ways;
(b) proximity and risk to/from other industrial facilities;
(c) present and future use of adjacent properties;
(d) handling and disposal of brine from salt caverns;
(f) topography and local and regional drainage of the site;
(g) proximity to environmentally sensitive wetlands or waters;
(h) access for emergency response;
(i) local weather conditions;
(j) proximity to other subsurface activities, e.g., neighboring storage or brine caverns or hydrocarbon production wells; and
(k) proximity of the boundary of the salt stock in Gulf Coast domes.

### 2.2.1 Distance Requirements

Distance requirements should provide for adequate surrounding salt to ensure cavern stability and containment of stored gas. Existing state regulations and/or site-specific geomechanical studies (such as laboratory tests on cores, numerical modeling, or field tests) should be used to determine distance requirements; or the following should be considered in the absence of appropriate regulations and/or studies:

(a) The distance between two adjacent solution-mined caverns in the formation should be a minimum S/D of 4:1, where S equals the distance between the centers of the two caverns and D equals the averaged value of the maximum diameter for each of the two caverns.
(b) The distance between any cavern center and the property boundary of an adjacent cavern field should satisfy 2.2.1(a) if all planned and existing cavern dimensions are known. Otherwise the distance to the adjacent property boundary should be a minimum of

2D from the cavern center, D being the maximum diameter of the cavern. In no case should the cavern wall be less than 100 ft from a property boundary.
(c) In salt domes, the distance between the cavern center and the salt stock boundary should be a minimum of 2D, where D is the maximum diameter of the cavern. At no point should the cavern wall be less than 300 ft from the salt stock boundary.

#### 2.2.2 Proximity to Rights-of-Way

All pipelines, railroads, highways, transmission lines, and any other utilities having rights of way that may affect the location or operation of the storage facility should be identified and appropriate measures taken to provide adequate protection within the design of the facility.

#### 2.2.3 Proximity to Underground Sources of Drinking Water

Underground storage operations should be conducted in a manner that does not adversely affect underground sources of drinking water.

# *3 DESIGN AND DEVELOPMENT CRITERIA*

## 3.1 ASSESSMENT OF NEIGHBORING ACTIVITIES

An evaluation should be made of all subsurface activities in the vicinity of the proposed storage operations that may negatively affect or be affected by the storage facility. Considerations should take into account: general safety, potential loss of product, subsidence effects, and possible environmental impacts. The following specific assessments should be made:
(a) potential for interaction with existing or abandoned wells within ¼ mi of the subsurface perimeter of the storage zone which may have a significant effect on operations;
(b) potential for gas migration into active or abandoned conventional mining activities within the area that possibly would be affected by the storage facility in bedded salt, and within the same dome in domal salt.

## 3.2 GEOTECHNICAL STUDIES

Site-specific data regarding the geology of the storage zone, surrounding formations and structures, and formations above and below the storage zone, should be assessed for suitability for storage of natural gas in salt caverns. The study should also include any available geophysical data relative to regional tectonic activity, regional and local fault zones, and structural anomalies.

The study should encompass all formations from the surface to the storage zone, and to a depth of 300 ft below the storage zone where such information is available, and all formations and structures for a minimum radius of ¼ mi from the subsurface perimeter of the proposed storage operations.

Studies for salt cavern storage should consider, but not be limited to

(a) regional stresses and strains;

(b) mechanical and chemical properties of the salt and confining rock formations based on core analysis, logging data, or other evaluation techniques;

(c) structural anomalies, including faulting, and regional dynamics of the formation; and

(d) cavern closure and stability, surface subsidence, and effects from neighboring activities.

## 3.3 MAPS

Cross-sectional and plan view maps should be obtained or developed for the planned facility which show the following:

(a) all wells and other manmade structures and activities within, and for a distance of ¼ mi around the subsurface perimeter of the storage caverns;

(b) regional and local faulting;

(c) in bedded salt the isopach of the host storage formation; and

(d) in domal salt the top surface contours, and also vertical sections of the salt stock and caprock through the cavern(s).

## 3.4 SUBSIDENCE

Potential ground subsidence for the proposed storage facilities should be assessed. The operator should design and implement a subsidence monitoring plan unless it can be shown that subsidence cannot affect the safety of the surface facility.

## 3.5 OPERATIONS

### 3.5.1 General

All available information on operating histories of local storage facilities should be reviewed to identify the potential for site-specific concerns.

### 3.5.2 Operating Pressure

Limits on operating pressure provide for safe containment of stored gas, cavern stability, and insignificant subsidence. Operating pressure limits should generally be based on existing state regulations, and/or site-specific geomechanical studies (as suggested in clause 2.2.1) or suitable testing; or the following should be considered where appropriate regulations and/or studies or testing are not available.

(a) The maximum operating pressure (psi) should be based on casing shoe depth (CSD) in feet, and should be limited to 0.85 CSD, or should otherwise be limited to 0.9 of confining stress at CSD calculated on the bases of the lithology and weight of the overlying formations.

(b) The minimum operating pressure (psi) should be 0.3 CSD (ft).

### 3.5.3 Maximum Injection and Withdrawal Rates

A study should be completed to determine maximum injection and withdrawal rates. Considerations should include

(a) cavern stability; and

(b) casing and tubing limitations.

# *4 WELL COMPLETION AND CONVERSION*

## 4.1 WIRELINE LOGS

An appropriate logging suite should be obtained for any well drilled for storage purposes to evaluate the suitability of the formation within and immediately above the storage zone for natural gas storage. Such a suite might include:

(a) Resistivity (induction)

(b) Spontaneous potential (SP)

(c) Density

(d) Neutron

(e) Gamma ray (run with neutron density)

(f) Velocity

(g) Caliper (shown on neutron density, may be run separately)

(h) Temperature

## 4.2 Core Acquisition and Formation Analyses

### 4.2.1 Formation Analyses

Care should be exercised in the conversion of existing salt cavern facilities to natural gas storage service. Sufficient evidence should be provided to establish the character of materials above and within the storage interval. Though coring may not be possible, character differences between natural gas and the materials previously stored should be addressed. Geomechanical effects of the proposed storage of natural gas relative to the previously stored products should be demonstrated. At least one well of a new storage facility should be cored to collect samples from the formation above the salt and from the salt section at the cavern roof, midheight, and bottom.

### 4.2.2 Core Handling

Every core taken should be
(a) extracted from the core barrel in accordance with good industry practices;
(b) placed in a core container strong enough to prevent breakage of the core; and
(c) accurately and durably labeled.

### 4.2.3 Core Analyses

Tests should be conducted on cores to determine the chemistry, lithology, and geomechanical properties of formations immediately above, within, and at depth of the natural gas storage cavern interval. Permeability measurements should be considered as well on cores of rock other than salt if there is a risk of gas migration through these nonsalt formations.

## 4.3 Casing Requirements

### 4.3.1 Design

Casing and cementing programs should be designed in accordance with current industry practice to provide well control and to avoid losses of stored natural gas or drilling fluids and potential contamination of fresh-water aquifers. (See API RP 1114, Design of Underground Storage Facilities, and API Bulletin 5C2.) Well casing design considerations should include:
(a) running and cementing of the casing;
(b) range of operating well pressures, flow rates, and temperatures;
(c) composition of the stored natural gas
(d) cyclic mode of operation;
(e) intended service of the well;
(f) stability of wellbore and corrosive fluid content of penetrated formations
(g) depth of the well.

#### 4.3.2 Service Conditions

Well casings should meet the specifications set out in API Specification 5CT. Potential exposure to hydrogen sulfide or other naturally occurring corrosive materials, either from natural gas content or from formation fluids, should be taken into account.

#### 4.3.3 Number of Casings

The following requirements should apply to avoid loss of stored natural gas:
(a) A minimum of one cemented casing should be set across all nonsalt formations.
(b) Two sets of casing should be set in salt into Gulf Coast salt domes, the first being set a minimum of 200 ft below top-of-salt, unless site-specific studies indicate otherwise.
(c) Two sets of casings should be set across all zones known to be corrosive to the casing over bedded salt formations.

#### 4.3.4 Liners

Liners should be designed in accordance with casing requirements and should have an overlap of 100 ft into the previous casing string.

#### 4.3.5 Inspection and Handling of Casings and Threads

(a) Casings should be inspected in accordance with API RP 5A5, and should be transported, stored, and handled in accordance with API RP 5C1.
(b) Casing threads should be inspected for gauge as per API RP 5B1, lubricated as per API Bulletin 5A2, and protected during casing handling.

#### 4.3.6 Running Requirements

The production casing should be run as per API RP 5C1. A casing guide shoe or equivalent shall be used to guide the casing and protect the end of the casing while running in the hole.

#### 4.3.7 Setting Depths

(a) In Gulf Coast salt domes, the production casing should be set into the salt at least 300 ft.
(b) In bedded and anticlinal salt formations, the production casing should be set into the salt a distance determined on the basis of a site-specific study that focuses on the competence and permeability of the overlying geological units.

#### 4.3.8 Pressure Testing and Records

(a) The casing should be tested for leaks and strength with test pressure equal to the maximum operating pressure measured at the wellhead; however, the pressure at any point along the casing should not exceed 80% of the casing burst pressure.

(b) Operators should retain in their files, for the life of each well, records of all pressure tests and any remedial actions taken.

#### 4.3.9 Casing Records

Operators should retain, for the life of each well, records of the following:
(a) casing tallies for all casing strings run
(b) casing inspection results

#### 4.3.10 Cathodic Protection

Operators should review the corrosion history of well casings in the same general area and consider the need for cathodic protection systems for well casings. Where appropriate, cathodic protection systems should be installed in accordance with current oilfield practice.

### 4.4 CEMENTING REQUIREMENTS

#### 4.4.1 Design

The cement program should be designed to isolate salt caverns from all permeable formations.

Well casing cement design considerations should include:
(a) types of formations being cemented;
(c) bottomhole pressure and related effects;
(d) bottomhole temperature and related effects;
(e) mud displacement; and
(f) casing centralization.

#### 4.4.2 Cement Tops

The following requirements should apply:
(a) surface casing should be cemented to the surface;
(b) intermediate casing, where installed, should be cemented to the surface where technically practical;
(c) production casing should be cemented to the surface where practicable; and
(d) the cement top should be verified by logging, unless cement is circulated to the surface.

#### 4.4.3 Cement Placement and Testing

Cement should be placed and tested in accordance with current industry practices.

#### 4.4.4 Cement Bond Integrity

A cement integrity log should be obtained if possible on the production casing to ensure competent bonding. The following requirements should be met:
(a) Neat cement should be allowed to cure for a minimum period of 48 hr prior to conducting a cement bond log (CBL).
(b) Lightweight cements with gel additives or entrained gases should be allowed to cure for a minimum of 60 hr prior to conducting a CBL.
(c) If a poor cement job is indicated, remedial cementing procedures should be taken before further completion if the well is attempted.

#### 4.4.5 Stage Cementing

Stage cementing should be permissible when the hydrostatic column of the cement exceeds the fracture pressure of the storage zone, or when zones of high permeability exist which could result in lost circulation.

#### 4.4.6 Remedial Cementing

The pressure and squeeze method of remedial cementing or other proven technology may be used to ensure isolation of the storage cavern if there is evidence of communication between the storage cavern or well and other horizons, but the perforated interval should be isolated by a patch or another casing or otherwise pressure tested to ensure that the perforations do not leak. Remedial cementing should be carried out according to current industry practice.

#### 4.4.7 Cementing Records

Operators should retain in their files, for the life of each well, all records related to both primary and remedial cementing.

### 4.5 Cased Hole Inspection Requirements

#### 4.5.1 General

Cased hole wireline logs should be taken in any well drilled or recompleted for storage purposes for proper evaluation of the storage well casing.

#### 4.5.2 Casing Inspection Logs

A casing inspection base log or an equivalent survey or test should be obtained over the entire cased interval for the innermost casing string or cemented liner in every well used for storage operations to verify the integrity of the casing.

### 4.6 Well Conversions

#### 4.6.1 General

All reentry and recompletion plans for converting existing wells drilled for purposes other than natural gas storage should ensure that all the requirements for new storage wells will be met; otherwise a detailed test plan should be developed for demonstrating the suitability of converting the existing wells to natural gas storage.

## *5 DEVELOPMENT (SOLUTION MINING)*

### 5.1 General

Salt caverns should be developed by solution mining (dissolution of salt with water). Critical to the development of salt caverns are control of the overall shape (to ensure mechanical stability) and protection of the cavern roof and casing seat from uncontrolled dissolution of salt. (For a description of solution mining of caverns in salt formations, see *SME Mining Engineering Handbook,* 1992.)

### 5.2 Cavern Shape

Cavern shape should be controlled during solution mining by hydrocarbon blanket material, water injection rate, water injection and brine removal locations, and salinity of injected water. Control may be facilitated by the use of computer simulations of cavern development. Evidence of cavern and roof shape control should be obtained during development by:
(a) monitoring and/or periodic verification of the location of roof blanket material;
(b) monitoring the total volume of salt removed from the cavern; and,
(c) sonar surveying of the completed cavern shape.

### 5.3 Intercavern Communication

Interconnected caverns should be treated and operated as a cavern gallery with the maximum dimension equal to the largest outside dimension of the gallery. Caverns with unusual shapes may be analyzed with geomechanical studies as per clause 2.2.1. Hydraulic fracturing or uncontrolled coalescence of caverns is not recommended for development of natural gas storage caverns.

### 5.4 CAVERN INTEGRITY

Cavern integrity should be ensured by the following test requirements:
(a) Prior to commissioning a cavern, a mechanical integrity test (MIT) should be conducted that demonstrates the integrity of the wellbore, the casing shoe, and the wellhead. The MIT should be a nitrogen (or gas) brine interface test (or equivalent) and should be conducted at maximum operating pressure. For caverns in salt domes located within 500 ft of the salt stock boundary, or in bedded salt where permeable interbeds are present in the storage interval, a brine pressure test should also be performed to verify cavern tightness. Where mechanical integrity of the cavern storage system cannot be demonstrated, the cavern should not be used to store natural gas.
(b) Mechanical integrity tests should be conducted periodically after the cavern is commissioned to demonstrate that integrity has been maintained. Test methods for these demonstrations may utilize less than maximum operating pressures, and may include

  (i) nitrogen (or natural gas) brine interface tests; or
  (ii) shut-in gas pressure tests

## *6 SURFACE FACILITIES*

See clause 1.6 regarding compliance with existing regulations on surface facilities. The following items should also be considered in the absence of any applicable existing regulations:

### 6.1 NONGAS STORAGE FIELD PIPING

Nongas storage field piping should be designed in accordance with current industry practices. Considerations should include
(a) intended service;
(b) temperature variations and potential movement of aboveground and buried pipe as per ANSI/ASME Standard B31.3.

### 6.2 WELLHEAD VALVES

Manual isolation valves should be installed on each wellhead. Each port on the wellhead should be equipped with a valve rated at a pressure rating that is the same or greater than the pressure rating corresponding to the maximum cavern pressure, or be fitted with a blind flange.

### 6.3 EMERGENCY SHUTDOWN VALVES

(a) Salt cavern storage facilities should be equipped with failsafe emergency shutdown (close) valves on all natural gas, blanket material, brine, or water outlets as applicable.
(b) Emergency shutdown valves should be capable of remote and local operation.
(c) Monitoring of valve position should be part of the valve installation.
(d) Emergency shutdown valves should be activated automatically by
  - (i) overpressuring in the natural gas system;
  - (ii) overpressuring or detection of natural gas in the brine or water system;
  - (iii) underpressuring in the natural gas system; or
  - (iv) detection of natural gas heat or flame.

### 6.4 MONITORING AND VENTING TUBING AND CASING

Access should be provided to each production casing and tubing string to provide pressure monitoring and venting capability.

### 6.5 CHOKES

Secondary access ports on the wellhead that are not protected by an emergency shutdown valve and which must remain open for monitoring or other purpose should have a choke device installed to limit the uncontrolled flow of natural gas from the well in the case of rupture, pipe failure, or instrument failure outside the wellhead valve.

### 6.6 DESIGN AND CONSTRUCTION

Design and construction of nongas storage surface facilities should be such that the possibility of explosion or fire damage to equipment or services necessary for the satisfactory operation of the emergency shutdown systems is minimized.

### 6.7 Relief Devices

Operators should consider protecting all piping and valves against thermal expansion of hydrocarbon or brine.

### 6.8 Instrumentation

The following instrumentation should be included as part of the control system to monitor storage operations for salt cavern storage facilities. Each of the following instruments should be connected to an alarm:

(a) flow indicators for natural gas or brine and;
(b) pressure indicators for both natural gas and brine located at the wellhead.

### 6.9 Wellhead Control Equipment

The following equipment should be included as part of the surface facilities:

(a) failsafe (close) actuators on remote-actuated emergency shutdown valves that are part of the emergency safety system;
(b) remote and local manual actuated emergency shutdown controls; and
(c) automatic actuated emergency shutdown controls.

### 6.10 Wellhead Enclosures

Where wellhead buildings are used and where a shelter covers equipment, ventilation should be provided to prevent accumulation of gases. Gas detection equipment should be installed to detect gas accumulation.

## *7 MATERIALS*

See clause 1.6 in regard to compliance with existing regulations on materials used in construction. Materials and equipment used in the construction of underground salt cavern storage systems should be in accordance with the requirements of all applicable state and federal regulations.

## 7.1 GENERAL DESIGN CONDITIONS

Materials used for pipe, tubing, casing, pumps, valves, electrical and safety equipment, instrumentation, and other components should be of sufficient weight, grade, and condition to satisfy the design conditions during construction and operation. Selection of materials should take into account depth of storage zone, operating pressure, surface and subsurface temperatures, intended service life of the project, and local geology. Wellhead equipment should comply with API Specification 6A.

## 7.2 SURFACE DESIGN TEMPERATURE

The minimum and maximum design temperatures should be taken to be at or beyond the lowest and highest expected temperature of the metal during pressure testing and service, having due regard for past recorded temperature data, the fluid temperature that could occur, and the possible effects of extreme air and ground temperatures.

## 7.3 ELECTRICAL CLASSIFICATION

All electrical and instrumentation components should conform to ANSI/API 500, or other codes that may apply.

## 7.4 QUALIFICATION OF MATERIAL

Insofar as methods of qualification for use under these guidelines are concerned, materials that do not comply with appropriate standards or specifications listed here may be qualified for use either by demonstration or technical data to ensure that they are safe for their intended service.

## 7.5 VALVES, FLANGES, AND FITTINGS

Steel fittings, flanges, and valves should comply with the applicable requirements of ANSI, API, and ASME, respectively, whichever is applicable. However, where components made to the requirements of these standards, whichever is applicable, are not available, it may be permissible to use fittings, flanges, and valves made to the alternative standards or specifications, provided that equivalency with this standard can be demonstrated.

# 8 *OPERATING AND MAINTENANCE PROCEDURES*

See clause 1.6 in regard to compliance with existing regulations on operating and maintenance procedures. In all cases, operators should have documented operating and maintenance procedures in accordance with all applicable state and federal regulations and as per API Standard RP750, and should have written copies available onsite for instruction and training of personnel.

## 8.1 Emergency Response Procedures

Operators should establish an emergency response plan in accordance with all applicable local state and federal regulations. The plan should include procedures for the safe control or shutdown of the natural gas storage facility in the event of a failure or other emergency.

## 8.2 Workover Procedures

(a) Blowout preventers with a pressure rating greater than 100% of the maximum operating pressure should be used. Blowout preventers should be stump-tested to a pressure in excess of the maximum expected pressure before installation.
(b) Snubbing units or similar equipment should be used where there is suspected pressure within the cavern.
(c) Wireline logging should be done through a lubricator unit suitably rated for the pressure of the cavern at workover.

## 8.3 Depressuring Procedures

Procedures should be developed to safely control depressuring of caverns. Such procedures should include monitoring for hydrogen sulfide and flaring as necessary if the hydrogen sulfide content of the gas exceeds 10 mol/kmol.

## 8.4 Records

Operators should maintain records and documents of all wellhead and primary safety maintenance and operations activities for a period of at least 5 years.

### 8.5 REVIEWS

Operators should review their operating and maintenance procedures at least once every 5 years to ensure that they are consistent with current industry and government standards.

### 8.6 INSPECTIONS AND TESTING OF SURFACE COMPONENTS

The following components of the facility should be inspected annually:
(a) instrumentation, valves, pumps, and emergency equipment;
(b) control systems;
(c) emergency shutdown valves; and
(d) wellheads and associated pressure monitoring systems.
Test results should be recorded and filed onsite.

### 8.7 INTEGRITY TESTING OF SALT CAVERNS AND CASINGS

Salt caverns and associated casings and wellheads should be tested for integrity prior to commissioning, 5 years after startup, and thereafter at 10-year intervals. Test results should be recorded and filed onsite. The initial mechanical integrity test should be performed with nitrogen-brine (see clause 5.4). All subsequent tests should be performed *in situ* (in place) with natural gas or by some other approved method.

### 8.8 CORROSION CONTROL

Corrosion control monitoring should be conducted to ensure the adequacy of the cathodic protection system.

## *9 MONITORING AND MEASUREMENT*

### 9.1 INVENTORY VERIFICATION

The operator should develop and implement the following procedures to verify the inventory in storage caverns. These include but are not limited to:
(a) measurement of all injected and withdrawn gas using industry accepted standards;

(b) maintenance of a continuous balance of inventory in storage for each cavern or cavern group joined by manifold by using the results of metering and comparing metering data with pressure/inventory strapping for each cavern;
(c) investigation of any losses or gains in inventory and the reasons for the variances. Should the losses or gains be due to migration of stored natural gas, the operator should undertake a study to review the integrity of the storage system and the impact of the migration.

### 9.2 Cavern Monitoring

Operators planning to solution mine under stored gas should develop a cavern monitoring plan on a case-by-case basis. The resultant monitoring information should be documented and retained onsite for the life of the storage operation.

### 9.3 Subsidence Monitoring

The operator should conduct subsidence monitoring as necessary as established per clause 3.4. Surveys should take place in the same season of the year to minimize the effects of ambient temperature.

## *10 SAFETY*

See clause 1.6 regarding compliance with existing regulations on safety.

### 10.1 Fire Prevention and Control

#### 10.1.1 Spacing of Permanent Equipment

Ignition sources should not be located within 75 ft of a well or unprotected source of flammable gas. Fires should not be located within 150 ft of a well or unprotected source of flammable gas.

#### 10.1.2 Control of Combustible Materials

All flare and well sites should be kept free of vegetation and combustible materials at all times.

### 10.1.3 Buildings

Buildings which contain sources of flammable gas should be constructed in accordance with all applicable state and federal building codes and regulations.

### 10.1.4 Flaring

Flaring, where required, should be conducted in the following manner:

(a) the flare line should terminate with a vertical riser of sufficient height and diameter to
- (i) prevent flame out and flame lift-off;
- (ii) ensure that any heat generated around the base of the riser does not endanger personnel or exceed the manufacturer's specifications for any equipment situated there or for any protective shielding/fencing to be installed;

(b) the flare line and riser should be anchored and provided with an approved means to keep the flame from being extinguished;

(c) the flare line should be provided with a vessel to separate and collect any liquids to prevent the liquids from reaching the flame;

(d) vegetation should be removed from the vicinity of the flare stack to a radius of twice the height of the flare stack.

## 10.2 Staff Training and Certification

Staff training and certification should be consistent with practices outlined in API Standard RP 750.

### 10.2.1 Wells

While a well is being drilled (or tested during drilling operations), completed, serviced, or reconditioned;

(a) one person who is qualified in well control should be onsite at the well; and

(b) the rig crew should have a thorough understanding of, and be able to operate, the well control equipment.

### 10.2.2 Storage Operations

Designated representatives of an operator at a storage well or facility should

(a) be qualified to provide competent and effective supervision of the operations being carried out;

(b) ensure that all personnel on the site are informed of the hazards and have knowledge of safety and emergency procedures; and

(c) ensure that all operating personnel are qualified to operate the facility.

### 10.2.3 Fire Fighting

All personnel directly involved in the maintenance and operation of underground storage facilities should be trained in fire safety.

## 10.3 Emergency Planning

Operators should develop an emergency plan to deal with accidental natural gas or brine releases, equipment failures, and natural perils and third-party emergencies. This plan should be documented and should include roles and responsibilities; emergency response procedures; and training, testing, and implementation requirements. The plan should be reviewed and tested in accordance with clause 8.1, and be subject to annual auditing.

## 10.4 Security

Security measures, including the installation of barricades, 6-ft small-mesh industrial-type steel fences, locking gates, security lighting, and/or alarm systems should be considered for wells and salt cavern storage facilities to prevent unauthorized access and protect the public.

## 10.5 Escape

Fences that surround wells at salt cavern storage facilities should have at least two gates located to provide a separate and convenient escape to a place of safety.

## 10.6 Identification Signs

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

## 10.7 Warning Signs

In areas that may contain accumulations of hazardous or noxious gas, the appropriate warning symbol should be displayed on a sign.

### 10.8 Voice Communication

Wellhead inspection and maintenance crews should have access to a direct communication link with the control room.

# *11 ABANDONMENT AND SITE RESTORATION*

See clause 1.6 regarding compliance with existing regulations on well abandonment.

### 11.1 Cavern Abandonment

#### 11.1.1 Gas Evacuation

Prior to abandoning a wellbore, the cavern should be evacuated, to the extent practicable, of all natural gas through displacement by saturated brine, or by fresh water if it is shown that the resultant cavern growth will not affect cavern stability or violate cavern spacing requirements. Brine injection and natural gas displacement operations should be conducted within the minimum and maximum pressure limits defined for cavern operations.

#### 11.1.2 Cavern Flushing

Following initial evacuation of natural gas, subsequent displacements should be performed until no significant additional natural gas is obtained. Where the cavern has been washed above the casing shoe, perforation above the shoe should be performed to permit recovery of additional natural gas.

#### 11.1.3 Salt Cavern Stability

The operator should develop an abandonment plan that includes demonstration of stability for all caverns being abandoned. The demonstration may include geomechanical analyses and/or analyses of brine outflow or pressure build-up for the cavern.

#### 11.1.4 Sonar Survey

Where possible, a sonar survey should be conducted prior to abandoning a wellbore to determine the final shape and areal extent of the cavern, if more than 5 years have elapsed since the previous survey.

### 11.1.5 Mechanical Integrity Tests

To ensure the integrity of the cavern, wellbore, and cement, before the plugs are set, a pressure test should be performed on the cavern and wellbore prior to abandonment if more than 5 years have elapsed since the previous test or if additional solution mining has occurred. If any significant leakage from the wellbore is detected, the owner should locate the leak and perform remedial work to ensure that cavern fluid will not migrate into other zones.

## 11.2 WELL ABANDONMENT

### 11.2.1 Well Abandonment Design

A well abandonment design should ensure that the storage zone is completely isolated from all other porous or hydrocarbon-bearing horizons.

### 11.2.2 Removal of Downhole Equipment

All downhole equipment and uncemented casing or tubing strings should be removed from the wellbore prior to starting wellbore abandonment operations, unless circumstances prohibit their removal.

### 11.2.3 Design and Placement of Initial Plug

The cavern should be isolated from the wellbore by a drillable bridge-plug, or a similarly effective sealing unit, located within 30 ft of the casing shoe or, in the absence of a casing shoe, within 30 ft of the end of casing, and should be pressure tested to the maximum anticipated differential pressure (MADP) across the sealing unit for 10 min, with no loss in pressure. The sealing unit should then be capped with circulated salt-saturated, sulfate-resistant cement of sufficient depth to cover two casing collars.

### 11.2.4 Wellbore Fluid

Fluid left in the wellbore between plugs should be of a quality such that, if released to a fresh-water aquifer in the quantities present in the wellbore, no adverse environmental impacts will result.

### 11.2.5 Additional Plugs

Additional plugs of cement should be located within the wellbore sufficient to cover or isolate all porous and permeable zones, including fresh-water aquifers, between the casing shoe and surface.

### 11.3 Surface Abandonment

Surface abandonment of the wellbore should consist of cutting the casing strings a minimum of 3 ft below ground level. Where surface casing is cemented to the surface, the production string should be plugged at the top with a 10-ft interval of cement; otherwise the production casing should be plugged with cement from a depth of 600 ft to the surface. Surface casing should be capped with a welded steel plate.

### 11.4 Surface Restoration

Surface restoration should return the surface to its original condition or as nearly as possible to its original condition.

## *12 ADDITIONAL ISSUES TO BE CONSIDERED IN FRAMING STATE REGULATIONS*

Is such storage geologically feasible in my state?
- Are suitable salt structures available?
- Are they located in areas suitable for industrial development?

Do the potential benefits of such storage to my state outweigh the risks and costs of administration?

Who should have responsibility for drafting necessary legislation, and for oversight?

What is the proper compliance schedule?
- When should it apply to new gas caverns?
- When should it apply to existing caverns?
- When should it apply to existing caverns being modified to gas storage?

Should projects be reviewed administratively, or at public hearings?
- Requirements
- Notice

What is the appropriate geological area for impact review?
- What things should be considered?

- To what distance should they be considered?
- What risk assessment method should be employed?

What certification will be required for data submitted in support of applications?

What physical tests will be required (in lieu of certification)?

What reporting and record keeping will be required?
- By the applicant
- By the state agency with oversight

What warning systems, alarms, training, and emergency response systems will be required?
- Of the applicant
- Of the state, or other agencies

What is the procedure for granting exceptions to policy?
- On the basis of extraordinary commercial merit
- On the basis of technical merit

What are the requirements for transfer of permits or of previously permitted facilities?

What are the penalties for noncompliance?

# *APPENDICES*

## *APPENDIX A. REFERENCE ORGANIZATIONS*

Codes, specifications, and standards of the following organizations are referred to in this guide.

**ANSI**
American National Standards Institute
11 West 42nd St.
New York, NY 10036
Phone: (212) 642-4900

**API**
American Petroleum Institute
1220 L St. NW
Washington, DC 20005
Phone: (202) 682-8000

**ASME**
The American Society of Mechanical Engineers
345 East 47th St.
New York, NY 10017
Order standards from:
The American Society of Mechanical Engineers
22 Law Drive
Fairfield, NJ 07007
Phone: 800-843-2763

**ASNT**
American Society for Nondestructive Testing
1711 Arlingate Lane
Columbus, OH 43228
Phone: (614) 274-6003

**ASTM**
American Society for Testing and Materials
1916 Race St.
Philadelphia, PA 19103
Phone: (215) 299-5400

**AWS**
American Welding Society
1950 NW 20th Ave.
Miami, FL 33125
Phone: (305) 324-6966

**AWWA**
American Water Works Association
6666 West Quincy Ave.
Denver, CO 80235
Phone: (303) 794-7711

**Gas Processors Association**
6526 East 60th Street
Tulsa, OK 74145
Phone: (918) 493-3875

**MSS**
Manufacturers Standardization Society
of the Valve and Fittings Industry
127 Park St. NE
Vienna, VA 22180-4602
Phone: (703) 281-6613

**NACE International**
National Association of Corrosion Engineers
P.O. Box 218340
Houston, TX, 77218-8340
Phone: (713) 492-0535

## *APPENDIX B. ADDITIONAL REFERENCE CODES AND STANDARDS*

The following codes, specifications, and standards may assist the developer of salt cavern facilities. In all cases the latest edition should be used.

**American National Standards Institute/American Society of Mechanical Engineers**
(ASNI/ASME) Standards
B31.3 *Piping in Chemical Plants and Petroleum Refineries*
B36.10M *Nominal Piping Size*
B16.5 *Pipe Flanges and Fittings*
B16.9 *Factory-Made Wrought Field Butt Welding Fittings*
B31.3 *Chemical Plant and Petroleum Refinery Piping*

**American National Standards Institute/American Petroleum Institute**
(ANSI/API) Standards
B500 *Classification of Location for Electrical Installations at Petroleum Facilities*
RP 520 *Recommended Practice for the Design and Installation of Pressure Relieving Systems in Refineries*
Part I--Design
Part II--Installation
RP 521 *Guide for Pressure Relief and Depressurizing Systems*
Bulletin 5A2 *Bulletin on Thread Compounds*
RP 5A5 *Field Inspection of New Casing, Tubing and Plain End Drill Pipe*
RP 5B1 *Recommended Practice for Gaging and Inspection of Casing, Tubing and Pipe Line Threads*
RP 5C1 *Care and Use of Casing and Tubing*
RP 1114 *Design of Underground Storage Facilities*
Bulletin 5C2 *Bulletin on Formulas and Calculations for Casing, Tubing, Drill Pipe and Line Pipe Properties*
Specification 5CT *Specification for Casing and Tubing*
Specification 6A *Specification for Valves and Wellhead Equipment*
RP 750 *Management of Process Hazards*

**American Society for Nondestructive Testing Publication**
Recommended Practice No. SNT-TC-lA
*Nondestructive Testing Personnel Qualification and Certification*

**American Society for Testing and Materials Standards**
E142-86 *Method for Controlling Quality of Radiographic Testing*

**American Welding Society Standard**
A5.2 *Specification for Iron and Steel Oxyfuel Gas Welding Rods*
*Code of Federal Regulations* Part 192

**Compressed Gas Association Publications**

**National Association of Corrosion Engineers**
MR-01-75 *Sulphide Stress Cracking Resistant Metallic Material for Oil Field Equipment*
RP-01-86 *Application of Cathodic Protection for Well Casings*

**National Fire Protection Association Publication**
No. 70--National Electrical Code

*SME Mining Engineering Handbook* 2nd ed., Vol 2, pp. 1493-1512, 1992.

# *APPENDIX C. IOGCC MEMBER STATE CONTACTS*

**Alabama**
Henry Moore
Petroleum Engineer, or
Richard Raymond
Manager
Petroleum Engineering Department
State Oil and Gas Board
420 Hackberry Lane
Tuscaloosa, AL 35486-9780
Ph: (205) 349-2852

**Alaska**
Blair Wondzell
Senior Petroleum Engineer
Oil and Gas Conservation Commission
3001 Porcupine Drive
Anchorage, AK 99501-3192
Ph: (907) 279-1433

**Arizona**
Steven L. Rauzi
Oil and Gas Program Administrator
Arizona Geological Survey
416 W. Congress St., Ste. 100
Tucson, AZ 85701-1315
Ph: (520) 770-3500

**Arkansas**
Hampton Bussey
Deputy Director
Oil and Gas Commission
P.O. Box 1472
2215 W. Hillsboro
El Dorado, AR 71731-1472
Ph: (870) 862-4965

**California**
Jim Campion
Technical Services Manager
Division of Oil, Gas and Geothermal Resources
Department of Conservation
801 K Street, 20th Floor
Sacramento, CA 95814-3530
Ph: (916) 445-9686

**Colorado**
Richard Griebling
Director
Oil and Gas Conservation Commission
1120 Lincoln St., Ste. 801
Denver, CO 80203
Ph: (303) 894-2100

**Illinois**
Lawrence Bengal
Office of Mines and Minerals
Dept. of Natural Resources
Division of Oil and Gas
P.O. Box 10140
300 W. Jefferson, Ste. 300
Springfield, IL 62701-1787
Ph: (217) 782-1689

**Indiana**
James A. Slutz
Director
Division of Oil and Gas
Department of Natural Resources
402 W. Washington Street
Room 293
Indianapolis, IN 46204
Ph: (317) 232-4055

**Kansas**
Nancy Heinz
Intergovernmental Coordinator
Oil and Gas Conservation Division
130 S. Market, Ste. 2078
Wichita, KS 67202
Ph: (316) 337-6200

**Kentucky**
Rick Bender
Director
Oil and Gas Division
Department of Mines and Minerals
P.O. Box 14090
3572 Iron Works Road
Lexington, KY 40512-4090
Ph: (606) 246-2026

**Louisiana**
Carroll Wascom
Assistant Director
Injection and Mining Division
Dept. of Natural Resources
P.O. Box 94275
625 N. 4th Street
Baton Rouge, LA 70804-9275
Ph: (504) 342-5515

**Maryland**
C. Edmon Larrimore
Acting Director, Mining Program
Water Mgmt., Administration
Dept. of the Environment
2500 Broening Highway
Baltimore, MD 21224
Ph: (410) 631-8055

**Michigan**
John King
Supervisor
Michigan Public Service Commission
6545 Mercantile Way
P.O. Box 30221
Lansing, MI 48909
Ph: (517) 334-7178

**Mississippi**
Lisa Ivshin
UIC/Technical Coordinator
State Oil and Gas Board
P.O. Box 1332
Jackson, MS 39215
Ph: (601) 354-7142

**Montana**
Thomas P. Richmond
Administrator/Petroleum Engineer
Board of Oil and Gas Conservation
2535 St. John's Avenue
Billings, MT 59102
Ph: (406) 656-0040

**Nebraska**
Bill Sydow
Director
Oil and Gas Conservation Commission
P.O. Box 399
922 Illinois
Sidney, NE 69162
Ph: (308) 254-6919

**New Mexico**
David Catenach
Petroleum Engineer
Oil Conservation Division
Energy, Minerals & Natural Resources
P.O. Box 2088
310 Old Santa Fe Trail
Santa Fe, NM 87504-2088
Ph: (505) 827-7132

**New York**
Clemsford A. Pollydore
Mineral Resources Specialist III
Division of Mineral Resources
Department of Environmental Conservation
50 Wolf Road, Room 290
Albany, NY 12233-6500
Ph: (518) 457-0100

**North Dakota**
Jack Wilborn
Assistant Director
Oil and Gas Division
Industrial Commission
600 E. Boulevard
Bismarck, ND 58505-0840
Ph: (701) 328-8020

**Ohio**
Thomas Tugend
Permitting Administrator
Oil and Gas Division
Department of Natural Resources
Fountain Square, Building A
3rd Floor
Columbus, OH 43224
Ph: (614) 265-6893

**Oklahoma**
Michael S. Battles
Director of Fuel Division
Oil and Gas Conservation Division
Corporation Commission
P.O. Box 52000-2000
Oklahoma City, OK 73105-2000
Ph: (405) 521-2302

**Pennsylvania**
James E. Erb
Director
Bureau of Oil and Gas Management
Department of Environmental Protection
P.O. Box 8765
Harrisburg, PA 17105-8765
Ph: (717) 772-2199

**South Dakota**
Fred V. Steece
Supervisor of Oil and Gas Programs
Dept. of Environment and Natural Resources
2050 West Main Street, Ste. #1
Rapid City, SD 57702
Ph: (605) 394-2229

**Texas**
David M. Garlick
Director of Research and Administration
TIPRO
515 Congress Ave., Ste. 1910
Austin, TX 78701
Ph: (512) 477-4452

**Utah**
James W. Carter
Director
Division of Oil, Gas and Mining
1594 W. North Temple, Ste. 1210
Salt Lake City, UT 84114-5801
Ph: (801) 538-5326

**Virginia**
Thomas Fulmer
Director
Division of Gas and Oil
Department of Mines, Minerals and Energy
P.O. Box 1416
230 Charwood Drive
Abingdon, VA 24212
Ph: (540) 676-5423

**West Virginia**
Theodore Streit
Chief/Commissioner
Div. of Environmental Protection
Office of Oil and Gas
#10 McJunkin Road
Nitro, WV 25143-2506
Ph: (304) 759-0517

**Wyoming**
Donald Basko
Retired Supervisor
Oil and Gas Conservation Commission
P.O. Box 2640
777 W. 1st Street
Casper, WY 82602
Ph: (307) 234-7147

**The Interstate Oil and Gas Compact Commission**
P.O. Box 53127
900 N.E. 23rd Street
Oklahoma City, Oklahoma 73105
Phone: 405/525-3556 Fax: 405/525-3592 E-mail: iogcc@oklaosf.state.ok.us