Hydrocarbon Storage in Mined Caverns

A Guide for State Regulators

A publication of the Interstate Oil and Gas Compact Commission
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FOREWORD

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

Because most states have not established regulations for mined cavern storage of hydrocarbons, and because accidents have occurred in other types of hydrocarbon storage facilities, it has been suggested that federal regulations might be necessary. However, a uniform federal regulation is not sound because geology and potential risks vary widely from state to state.

Similarly, the potential rewards of hydrocarbon storage do not fall evenly on all states. More fundamentally, we believe that balancing reward with risk in state resource development should remain a matter of state policy. If states proactively regulate mined cavern storage of hydrocarbons, risks can be minimized and federal regulations should be avoided.

The IOGCC recognized an opportunity to serve its membership by developing guidelines for the regulation of hydrocarbon storage in mined caverns. Discussions were held regarding such guidelines at the Energy Resources, Research and Technology Committee meeting in June 1999. At that time we formed a subcommittee to:

- Propose performance guidelines.
- Identify regulatory issues.
- Identify associated regulatory references.

Our subcommittee is composed of state regulators as well as professionals from the industry. Their diverse ideas, input and comments were invaluable in creating this document. On behalf of the IOGCC, I want to thank those who assisted with this project. I personally wish to thank our subcommittee co-chairs, James E. Erb and Steve M. Mayo, whose efforts made this report a reality.

John T. King
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About the IOGCC

The Interstate Oil and Gas Compact Commission represents the governors of 37 states — 30 member and seven associate states — that produce virtually all the domestic oil and natural gas in the United States. Five international affiliates have been accepted into the IOGCC in recent years.

The organization's mission is to promote the conservation and efficient recovery of domestic oil and natural gas resources, while protecting health, safety and the environment.

Since its creation in 1935, the IOGCC has assisted states in balancing a multitude of interests — maximizing domestic oil and natural gas production, minimizing the waste of irreplaceable natural resources, and protecting human and environmental health — through sound regulatory practices. The IOGCC plays an active role in Washington, D.C., serving as the voice of the states on oil and natural gas issues and advocating states' rights to govern the resources found within their borders.

For more information about the IOGCC, please call 405/525-3556, visit its Web site at www.iogcc.state.ok.us, or send e-mail to iogcc@iogcc.state.ok.us

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Alabama, Alaska, Arizona, Arkansas, California, Colorado, Florida, 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, Missouri, North Carolina, Oregon, South Carolina, Washington

International Affiliates

Alberta, Egypt, Newfoundland and Labrador, Nova Scotia, Venezuela
ACKNOWLEDGMENTS

We would like to thank the following workgroup members of the Hydrocarbon Storage subcommittee of the IOGCC Energy Resources Committee for their suggestions and review of the guidelines and definitions sections. These individuals made valuable contributions in preparing these guidelines:

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DEFINITIONS

The following definitions are used in this guide:

**Abandoned well** — a well that has been permanently deactivated.

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

**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.

**Bore hole** — a hole made by drilling or boring.

**Bottom hole** — the lowermost portion of the well.

**Casing** — metallic or nonmetallic pipe placed in the borehole to support the sides of the bore, to prevent subsurface migration of fluids out of or into the borehole and to permit the controlled flow of fluids through the borehole.

**Casing inspection log** — a log or combination of logs which provides an indication of the thickness of metal remaining in the casing and the deformation (ovality) of the casing by measuring:
   (a) the depth of penetration of anomalies into the well casing.
   (b) external and internal corrosion.
   (c) pits, perforations, metal loss and metal thickness.
   (d) deformation or ovality.

**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.

**Catastrophic release** — the release of 10,000 pounds or more of stored hydrocarbons.

**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.

**Cavern** — a natural or manmade opening in the subsurface.
Cavern storage facility – an operation storing hydrocarbons in one or more caverns and including piping, surface equipment, structures and the site area.

Cavern storage zone – the vertical interval of a cavern and the lateral extent of formation directly affected by the storage operation.

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:

(a) firmly fix the casing in the hole.
(b) buttress the casing string against formation, production or injection pressures.
(c) provide lateral support against tensional loads on casing.
(d) protect the casing from corrosion caused by exposure to formation fluids.
(e) provide a seal against flow of fluids in the annular space.

Cement integrity log (typically referred to as a cement bond log) – a downhole geophysical evaluation survey used to indicate the quality and quantity of cement bonding between casing and rock formations.

Communication – the movement of fluids (gas, water, or hydrocarbons) through porous and permeable strata 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 continue to confine fluids to an injection interval, cavern, or well bore.

Depressurize – the lowering of pressure within a cavern, vessel or pipeline by the removal of fluids.

Drawdown – the removal of inventory or lowering of pressure.

Drift – a horizontal underground opening that follows along the length of a vein or rock formation.

Drilling – all technical activities connected with the construction of a well.

Flow rate – the flow of a fluid in terms of volume or mass per unit of time.

Fluid – any material or substance that flows under low deviatory stress and is in a semisolid, liquid, sludge-like, 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 that, if applied to subsurface formations, will cause the formations to fracture.

Fresh-water strata – porous and permeable, fresh-water-bearing rock or unconsolidated material.

Gallery – A horizontal or a nearly horizontal underground passage, either natural or artificial.

Geotechnical Evaluation – all technical activities connected with the investigation of geological, hydrological and seismological conditions of a site.

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, 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.

Hydraulic fracturing – a method of fracturing formations with fluid injected at high pressures. Sometimes used to determine the magnitude and direction of principal horizontal stresses in rock.

Hydrocarbon – organic compounds of the elements hydrogen and carbon whose densities, boiling points, and freezing points increase as their molecular weights increase. The simplest hydrocarbon is methane, CH₄. Hydrocarbons that may be stored also include crude oil and products of petroleum refining (e.g., liquefied petroleum gas (LPG), olefins, gasoline, naphtha, benzene, kerosene, diesel and lubricating oil).

Injection well – a well specifically designed to inject fluids into the subsurface.

Interface – a surface that forms a boundary between two distinct fluids in a cavern (e.g., between water and the liquid hydrocarbon in storage, between the liquid hydrocarbon and vapor hydrocarbon) or a well.

Intermediate casing – a pipe, usually metallic, placed in the bore hole 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 zones or non-competent rock formations prior to drilling into the storage zone.

Isopach Map – a map depicting areas of equal thickness of subsurface geological formations.

Liner – casing normally installed within production casing for remedial repairs.
Liquefied Petroleum Gas (LPG) – Light hydrocarbons, typically C₂-C₄ existing as gas at surface temperature and pressure and stored as a liquid under pressure. It mostly concerns propane and butane, or mixtures of the two produced commercially from petroleum or natural gas.

Lithology – the description of physical characteristics of rock formations.

Lithostatic Pressure — The vertical pressure at a point in the earth’s crust equal to the weight of the overlying column of rock.

Log – a systematic recording of data, such as a driller’s log, mud log, electrical log, or radioactivity log. Many different logs are run in wells to obtain various characteristics of downhole formations. 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, for determining cavern or well integrity.

Logging – measurement of any physical parameter versus depth in a well.

Mechanical integrity test – a procedure that determines if 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 another formation or cavern.

Mined formation – a rock formation from which some rock material has been removed.

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

Overburden – all formations and fluids overlying a storage zone.

Permeability – the measure of the ability of fluid to flow through connected pore spaces of rock.

Pillar – a descriptive term applied to the residual unmined rock between mined openings acting as both separating wall and roof support in adjacent cavern spaces.

Porosity – the state or quality of being porous; the ratio of the volume of the fluid-filled pore space within a formation to the total volume of the solid rock indicating how much fluid a rock can hold.

Production casing – a pipe, usually metallic, placed in the bore hole 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 mined formation used for storage.
**Rock** — any naturally formed indurated aggregate of mineral matter, constituting an essential and appreciable part of the earth's crust. Rocks are divided into three groups on the basis of their origin: igneous, metamorphic, and sedimentary.

**Room and Pillar** — a mining method in which rock is removed from a formation in a pattern. The room and pillar method in its basic form consists of driving entries, rooms and crosscuts into the formation to extract rock. Pillars of rock are left to support the cavern roof. Movements of the ground surface during this procedure are nearly always imperceptible. Generally, rooms are 12-30 feet wide and the pillars up to 100 feet wide. As mining advances, a grid-like pattern of rooms and pillars is formed, Figure 1.

![Figure 1: Room and Pillar Construction](image)

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

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

**Subsidence** — Earth movement that occurs when a patch of land over an underground [cavern] sinks, shifts, or otherwise changes its configuration. (Adapted from U.S. Court of Appeals, District of Columbia, *National Coal Mining v. Bruce Babbit*, U.S. Department of the Interior, No. 98-5320)

**Surface casing** — a pipe, usually metallic, placed in the bore hole and cemented into place to control a well and protect underground sources of drinking water (USDW) from damage during drilling, mining or production operations.
**Tubing** – the small diameter pipe (2" and 2½" are common) inside the casing that provides the conduit through which oil and gas is produced to the surface.

**Water Curtain** – An area of water surrounding a cavern where the pressure has been artificially raised above the normal hydrostatic pressure. The pressure is normally raised by installation of bore holes and pumps.

**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, mechanical, acoustic or radioactive methods; measurements are made in the well with the devices connected by a wire cable to monitoring equipment on the surface.
1. HYDROCARBON STORAGE IN MINED CAVERNS

1.1 Introduction and Scope

Whereas the Department of Transportation's Office of Pipeline Safety has jurisdiction over the design, construction, operation and maintenance of hydrocarbon transmission lines and distribution facilities, it does not have jurisdiction over mined cavern storage facilities. There are no guidelines to help state regulators develop standards. Drawing up such regulations is a daunting task for states with little or no experience in this area. The guidelines in this document have been prepared to help state regulators and industry address the operational and safety problems of storing hydrocarbons in underground mined caverns.

Mined caverns make excellent low-cost storage containers for hydrocarbons. Properly constructed caverns ensure that the contents do not migrate. Mined caverns that can store large quantities of hydrocarbons under moderate pressure can be developed at costs that are less than surface storage.

Existing open space in abandoned mineral mines can be utilized for hydrocarbon storage or new space may be excavated, using traditional drill and blast techniques or by using boring machines. Cavern shapes can vary between a series of large connected drifts and traditional room and pillar construction. The formation must have adequate properties to ensure that the stored hydrocarbons cannot migrate beyond the mined space.

1.2 Benefits of Mined Cavern Storage

Mined caverns that are properly located, constructed and operated can help the oil and gas industry become more cost competitive by reducing capital requirements and operating costs.

Where available, mined caverns are inexpensive mechanisms for modulating hydrocarbon flow. The costs per pound of stored material for the services provided are lower because caverns provide large storage volume, high flow rates and handle liquids almost exclusively.

Cavern Well

The storage cavern is connected to the surface through a well or wells. A cavern well is the conduit through which hydrocarbons are injected and withdrawn from the mined caverns. The well is composed of a wellhead and casing cemented to the surrounding rock. It also might be completed with tubular strings set on hangers in the wellhead. The cavern well and all components must provide a barrier that prevents the migration of fluids and resists inside or outside deterioration through corrosion or geomechanical stress.
One of the most critical phases in the completion 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.

**Geomechanical Stability**

A mined cavern is subject to differential stress as a result of the difference between the pressure from the formations surrounding the cavern and the pressure within the cavern. The cavern shape and dimensions, the thickness of rock overlying the cavern and the distance between the storage cavern and neighboring caverns resist the differential stress and hence affect its stability.

The weight of overburden material generates lithostatic pressure, which is generally close to one pound per square inch (psi) per foot of depth. The local stress distribution also can be affected by the tectonics specific to the location. For instance, geologic movement, such as lateral thrusting can deform the rock formation. Because 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 rock formation and its surroundings.

The relative magnitudes of horizontal and vertical stress and directions of maximum and minimum horizontal stress can be evaluated by hydraulic fracturing in boreholes.

**Roof Collapse**

The roof of the cavern, if improperly designed, may be the component subjected to tensile stress. Rock is usually resistant to compression, but not to tension. When a cavern is developed with an overly extended flat roof, tensile stress is concentrated above the cavern. The cavern’s integrity can be seriously endangered if the unsupported roof were to collapse. Proper roof design aims at minimizing tensile stress around the excavation.

**Pillar Collapse**

Cavern stability also depends on the percentage of rock left unmined as pillars. In the "room-and-pillar" technique, if not enough properly distributed pillars of adequate size are left to support the cavern, the pillars and cavern might collapse.

**Surface Subsidence**

Subsidence usually will occur at the surface as the result of convergence or collapse. If subsidence is too great and too rapid, it might affect the surface facilities, buildings, equipment and piping. The collapse of a roof or cavern can result in sudden major subsidence at the surface and the formation of sinkholes over the cavern. This
could destroy surface equipment and allow hydrocarbons to migrate to the surface or to underground sources of drinking water.

1.3 Scope of This Document

Whereas the U.S. Department of Transportation (DOT) has jurisdiction over the transmission and storage of hydrocarbons, responsibility for enforcing the safety of storage facilities has been left to the states. The DOT has provided no guidance for the regulation of underground storage. However, many states have little experience in the area of gas storage in mined caverns. The states should regulate mined storage because there are extreme variations in geology from state to state.

Guidelines in this document are based on industry practices, existing state rules and on regulations developed by the Canadian Standards Association. Minimum design, construction, operation, abandonment and safety aspects of storing hydrocarbons in mined formations are covered. Subsurface equipment, the wellhead and all safety equipment related to storage facilities, wells and wellheads are also covered. The guidelines do not apply to:

- Underground storage facilities for materials other than hydrocarbons.
- Underground storage of hydrocarbons in structures other than mined caverns, i.e., solution-mined storage, hydrocarbon 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 mandate any one specific cavern system design to prevent development of new equipment or practices, or to prescribe how such innovations should be handled.

1.4 Conclusion: The Need for Regulation

A review of the critical components of hydrocarbon storage in mined caverns reveals the need for regulating (1) cavern construction, (2) conversion of mines to hydrocarbon storage, and (3) cavern operation.

Construction and Operation of New Caverns

Regulatory guidelines must be established for the various stages of the construction and operation of a new cavern. At the planning stage, it is necessary to ensure that the design of the wells for each cavern (if more than one is planned) and overall facility meet the standards of the industry. This must be based on a geological review of the location that is sufficiently extended in depth and area to cover the
features affecting the storage caverns and wells. In addition, the design of caverns and cavern wells must be based on detailed knowledge of the geology and hydrology of the location, obtained through coring the potential cavern host rock and conducting borehole hydraulic tests and performing laboratory tests on representative cores to determine pertinent engineering properties. Examples of engineering properties include:

- Permeability to air (horizontal and vertical).
- Permeability to hydrocarbon (horizontal and vertical).
- Apparent porosity.
- Compressive strength.
- Water-air slaking.
- Hydrocarbon slaking.
- Specific gravity.

1. **Permeability to air**

The plugs are secured in rubber stopper sleeves, and the volume of air flowing through the core is measured with a meter, or by water displacement, depending upon the rate of flow. The maximum pressure differential used is 30 psi. Cores through which no air will flow for a period of one minute are considered as having permeability of zero.

2. **Permeability to hydrocarbon**

The same procedure is used for the hydrocarbon proposed for storage, except that the maximum pressure differential used is 50 psi, and the tests on plugs which are permeable are conducted for one hour, taking volume-time readings every fifteen minutes.

3. **Apparent porosity**

The porosity is measured the second day after the plugs are cut. By obtaining the dry weight, C Cl₄ (carbon tetrachloride) saturated weight, and bulk volume, the porosity can be calculated. To ensure the filling of all pores, the cores must be saturated with C Cl₄ and subjected to a pressure of 1000 psi for ten minutes.

4. **Compressive strength**

The compressive strength is measured by using a hydraulic compressive tester.

5. **Water-air slaking test**

The test is performed by immersing representative sample in water for 12 to 15 hours, and exposed to air from five to seven hours. This cycle is repeated for five days. An initial observation is made approximately two hours after the samples are immersed in water.
6. **Hydrocarbon slaking test**

Representative samples are selected and immersed in the proposed hydrocarbon to be stored for five days, and inspected after the five-day period.

7. **Specific gravity**

The specific gravity is measured the second day after the plugs are cut. The specific gravity is obtained by dividing the dry weight of the plug by its bulk volume. This value is not the true specific gravity of the sand grains. Instead, it gives the specific gravity of the formation in place.

Optional borehole geophysical logging, especially in the case of sedimentary rocks, is useful for rock correlation and determination of rock properties. Finally, the geomechanical stability of the cavern(s) must be addressed by geomechanical analysis techniques (usually two-dimensional or three-dimensional finite-element computer codes) supported by adequate geomechanical core data. Three-dimensional analysis might be needed when a cavern or its surroundings are not axisymmetric.

During construction of the cavern wells, inspection and testing procedures should verify the integrity of the cavern well after drilling and prior to mining, and the integrity of the cavern and final casing shoe after mining and before the cavern is filled with hydrocarbons. These tests should follow recognized industry practice.

During operation of the cavern, records must be kept and made available to the appropriate regulatory commission. These should include operational parameters and monitoring of the environmental parameters related to stability and tightness.

**Conversion of Existing Mines to Hydrocarbon Storage**

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

1.5 **Existing Regulations**

If these guidelines are at variance with the requirements of existing standards or codes, those standards should govern. This statement should be noted in particular for 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 they are incorporated into regulations promulgated by state agencies responsible for overseeing hydrocarbon storage. In most cases, the storage cavern and the wellhead up to the outlet of the "wing valve" should be regulated by the state. DOT
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.

2. LOCATION OF MINED 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 and/or use of underground water resources. 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:

- Proximity to populated areas and public rights-of-ways.
- Proximity and risk to/from other industrial facilities.
- Present and future use of adjacent properties.
- Present and future use of aquifers.
- Topography and local and regional drainage of the site (flood potential).
- Proximity to environmentally sensitive wetlands or waters.
- Access for emergency response.
- Local weather conditions.
- Proximity to other subsurface activities, e.g., neighboring drilling, storage, mining activity or water production wells.

Please note that finding a suitable site with appropriate geological characteristics is a prerequisite.

2.2.1 Distance Requirements

The minimum distance between adjacent caverns shall be chosen to ensure structural stability and product containment and prevent the migration of stored products from one cavern at operating pressure to an adjacent cavern at atmospheric pressure. The hydrogeological protection perimeters around the storage caverns restricting drilling or underground works in the protected area must be defined.
2.2.2 Proximity to Rights-of-Way

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

2.2.3 Proximity to Underground Sources of Water

Underground storage operations must not adversely affect underground sources of water. Adequate monitoring of cavern operation and of any activity within the protection perimeter is required.

3. CRITICAL COMPONENTS OF HYDROCARBON STORAGE IN MINED CAVERNS

The most stringent conditions for storing hydrocarbons (apart from compressed gas) are found when dealing with LPG due to their relatively high vapor pressure. Therefore a special focus will be put hereafter on LPG.

3.1 Technical Description

LPG is stored underground in a mined rock cavern of stable construction, made up of one or more galleries excavated from an access shaft or tunnel at a depth which ensures the containment of the stored LPG. Product movements are achieved through various lines installed in one or more operation shafts or auxiliary wells connecting the storage space to the surface.

The storage caverns are made up of a series of workings, or galleries, laid out in a particular design pattern. The prevalent historical U. S. design has been room and pillar. Another design, popular in Europe and other parts of the world is that of one or more main galleries, commonly parallel, linked together by connection galleries of generally smaller dimension. Connection galleries allow circulation of personnel and equipment during construction (excavation), ventilation and later movement of water and the stored product. Connection galleries contribute to storage capacity. The most commonly used excavation method in hard rock is drilling and blasting. Alternative methods include roadheaders or tunneling machines. The excavation method is determined by the rock mass properties, the size of the excavations and the cost and availability of equipment.

Ancillary surface facilities encompass equipment specific to LPG underground storage such as coalescers, dryers and seepage water strippers. Also used is equipment commonly encountered in surface LPG storage plants such as marine, road or rail loading/unloading facilities, heaters, metering units, pipes, firefighting systems, gas detectors, control room and centralized process computer system, buildings, shelters, etc.
The principle of underground storage reduces the risk of fire and explosion, because no air is present in the cavern during operation and because the large volume of LPG stored cannot be exposed to fire, explosion, or Boiling Liquid Expanding Vapor Explosion (BLEVE). Furthermore, underground caverns historically are resistant to earthquakes. The stored product is located at depth, is safely contained within the excavated cavern space and is isolated from the surface.

3.2 Geology

Underground storage facilities must be stable, leak tight and neutral to the stored product.

Sites are selected essentially on criteria developed through geological evaluation: Is the rock formation hard enough, tight enough and at a suitable depth, with a sufficient natural water table recharge?

- The rock must be strong enough for the cavern to be stable. A wide range of different rocks can be considered: granite, gneiss, sandstone, limestone, chalk, shale, etc.
- If the cavern wall is not lined, the rock is kept exposed. LPG is prevented from escaping on the principle of hydraulic containment, whereby the cavern is located at such a depth that the water present in the surrounding rock exerts a pressure towards the caverns that is greater than the pressure of the LPG, preventing the LPG from migrating. The depth of the facility is governed by the vapor pressure of the LPG. Water pressure in the rock can be enhanced artificially by special water supply systems (water curtains).

3.3 Cavern Stability

Mined storage caverns are stable chiefly because the geological and geomechanical properties of the host rock and mined openings are strong enough to withstand pressure conditions when in operation.

Stress analyses make use of field data gathered during the site survey, laboratory test results and modeling. Similar studies predict the stress pattern around multiple caverns side-by-side, intersections, sumps, access and/or operating shafts, tunnel and shaft plugs. Therefore, the best cross sectional shape for cavern stability can vary considerably with different rock properties.

These studies are the basis for deciding the best orientation of the caverns and what support (rock bolts, shotcrete) should be applied during excavation.
3.4 Hydraulic containment

Mined caverns used for the storage of hydrocarbons usually are excavated in hard rock. The rock mass hosting the cavern cannot be considered impervious to liquid or gas (except in few favorable cases of clay or clay-rich rock and rock salt) because of the widespread distribution of pores and fissures including those created by the construction process (cracks from blasting, for instance).

Rock improvement techniques such as grouting or by lining to improve tightness has not typically been used as the sole means of containment because of their unreliability and/or their high cost (steel lining of the underground cavern, for instance). Advances in technology for these techniques may change either their reliability and/or cost. Application of new techniques should be made through appropriate reviews such as Process Hazard Analysis (Section 12.9).

The underground storage of liquid and gaseous hydrocarbons is based on the principle of natural hydraulic containment.

Expressed simply, to ensure the containment of the stored product, the pressure in the cavern has to be lower than the pressure of water on the cavern. However, the real hydraulic containment principle is based on a potential criterion rather than on a pressure criterion.

Hydraulic containment occurs when the hydrostatic pressure of the groundwater in the host rock exceeds the vapor pressure of the stored product. This requires an uninterrupted flow of groundwater inwards towards the cavern, thus preventing the stored product from migrating outwards.

The storage cavern must lie below the water table, at a depth dictated by product pressure at the temperature of the host rock at that depth, the hydrogeological properties of the rock at the site and the geometry of the underground works. In some cases, horizontal and/or vertical water curtains, can be provided to enhance the permanent groundwater flow towards the storage caverns. A horizontal water curtain might consist of a small section gallery, generally located above the storage caverns, from which bore holes are drilled. A vertical water curtain consists of vertical or subvertical bore holes drilled from the surface, or from a purpose-designed gallery. The vertical water curtain is used mainly to avoid hydrogeological interference between two or more storage caverns, and to allow independent operation of each.

Containment principle can be expressed as follows: $H > P + M$, in which:
- $H$ is the hydrostatic pressure at the highest point of the cavern.
- $P$ is the potential (vapor pressure) of the stored product under operating conditions.
- $M$ is the safety margin.
Particular attention must be given to ensuring that the rock remains saturated with water during excavation and operation of the facility. Piezometers placed at and around the storage cavern site monitor the level of the water table to insure a constant supply of inwardly flowing water.

**Figure 2: Typical Cavern Installation**

3.5 **Connecting Lines / Wells**

These facilities are operated using a system of wells to inject and withdraw the LPG, and make the necessary checks and measurements.

The underground storage space is connected to the surface by a series of wells accommodated in one or more operation shafts or in operation wells that are drilled, cased and cemented. They include:
- Inlet line(s).
- Outlet line(s) fitted with submersible pump(s) or line shaft driven pump(s) for product delivery.
- Seepage water line(s) and pump(s).
- Instrumentation line(s).
- Vent line(s).
When installed in a shaft, the operation pipes might be anchored in a concrete sealing plug located immediately above the cavern crown. After pipe installation, the shaft may be flooded with water for the operation phase.

It is recommended that these lines be equipped with safety devices. Permanent adequate corrosion protection and periodic relevant control are required.

### 3.6 Maximum Operating Pressure

Before operation start-up and first LPG filling, the cavern is air tested at a test pressure higher than the Design Maximum Working Pressure.

The cavern test pressure is therefore set with reference to:

- Hydrogeological factors.
- Operating conditions.
- Maximum allowable operating pressure.

The test must demonstrate that the cavern is gas-tight. It consists of recording pressure changes over time, which must coincide with (to within the experimental error) the pressures calculated for a non-leaking cavern, i.e. pressure changes must be caused solely by air temperature variations in the cavern and, if applicable, water level changes in the sump.

Maximum allowable operating pressure is a critical parameter, which must never be exceeded. To cope with this fundamental requirement, continuous monitoring of cavern pressure and automatic shutdown sequences in case of abnormal upset conditions at archival preservation are required.

### 3.7 Monitoring

Throughout the operation, the stability of the structure might be checked by continuous surveillance of acoustic emissions (seismic monitoring), and its LPG-tightness by a hydrogeological monitoring system through observation wells (piezometers and pressure cells).

The prime purpose of hydrogeological monitoring of unlined underground storage caverns is to check that hydrogeological conditions necessary for hydrodynamic containment of the stored product are maintained at all times.

The hydrogeological parameters to be observed over the lifespan of the facility, and the method of processing the associated data, must insure day-by-day confirmation of hydraulic containment performance and, more importantly, provide advance warning of any likely deficiencies. This second aspect is called preventive monitoring, and is based on an understanding of the hydraulic behavior of the facility and correct interpretation of any detected changes in the hydrogeological parameters.
Owing the vital importance of monitoring for safe storage, the monitoring equipment needs to meet precise, well-defined performance criteria, which dictate its choice, installation and monitoring practice.

Hydrogeologic monitoring should be conducted throughout the life of the storage project. Initially, the geotechnical feasibility study test holes will provide the primary hydrologic data such as water table and piezometric levels necessary for planning the optimum cavern depth. If a site proves feasible for construction, some or all of the feasibility test holes could be completed as monitor holes for future use. If necessary, additional monitor wells could be added in the cavern area.

Monitor holes would be used to check water table and direction of ground water movement and to detect any hydrocarbons escaping from the cavern.

Hydrogeologic monitoring should be initiated prior to cavern construction, then continued during construction and over the entire operational life of the cavern. If seismic or subsidence monitoring is considered advisable it should be initiated in the construction stage and continued throughout the operational period.

4. **DESIGN AND DEVELOPMENT CRITERIA**

4.1 **Design Principles**

Surface and subsurface installations must be designed to control the process and utility fluids at any combination of pressure and temperature to which they might be subjected, within a determined range of operating conditions. They must fulfill existing standards for the individual parts of a storage system.

Analysis and calculations shall be made using proven technology, and all relevant data should be documented.

Oil and gas industry and mining industry proven technology will be adhered to where applicable.

All relevant data concerning cavern design such as cavern gallery dimensions and layout, equipment specification and operating procedures should be documented and available to the owner and the operator of the storage facility. Adherence to safety and environmental requirements shall be monitored by the operator.

A properly constructed and maintained cavern shall be as safe or safer than the surface facilities associated with it.

4.2 **Assessment of Neighboring Activities**

An evaluation should be made of all subsurface activities in the vicinity of the proposed storage operations that might 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:

- Potential for interaction with existing or future activity within a prescribed distance from the perimeter of the storage zone, which may have a significant effect on water table level.
- Potential for migration of hydrocarbons.

4.3 Geological Evaluation / Geotechnical Studies

Site-specific data regarding the geology of the potential storage zone, surrounding formations and structures, and formations above and below the mined cavern, should be assessed for suitability for storage by adequate means such as geological and geophysical surveys, drilling operations, tests, water analyses, etc. The study should also include any available geophysical data relative to regional tectonic activity, regional and local fault zones and structural anomalies.

It is recommended that available geological and hydrogeological data as well as local engineering knowledge and experience in underground works (e.g. existing tunnels, sewage galleries, etc.) be gathered in a pre-feasibility study. This study shall also include the proposed project basic data, such as product to be stored, contemplated storage pressure and capacity, yearly turnover, etc.

The evaluation study shall focus on:

- The geological definition of the rock mass from surface to below the proposed storage depth (type of rock, characteristics).
- The definition of the local structural features in relation to the local and regional tectonics (jointing, existence of regional or local faults, structural anomalies, etc.).
- The definition of the geotechnical characteristics of the rock mass (i.e. strength, joint pattern, swelling properties, in-situ stresses, etc.).
- The definition of the hydrogeological site characteristics (porosity, permeability profiles and distribution, heterogeneity, aquifer characterization, relation between aquifers, etc.)
  1. Hydrostatic head within the wells in the area that might be affected during construction shall be measured.
- The demonstration by compatibility tests that there is no unacceptable chemical interaction between the stored product and the surrounding geological formations, which could lead in the long term to decay of the product or to alteration of its characteristics; conversely, the product shall not adversely impact the rock mass characteristics.
- The definition of the initial in-situ conditions. Suitable analyses shall be conducted on sufficient samples representative of the water from each aquifer concerned during field investigation or before the project is started, to
demonstrate that water quality has not been affected by construction materials or operations.

- The definition of the local and regional seismic hazard.

This information shall be collected by some or all of the following means, to suit local site conditions:

- Documentary research.
- Geological mapping.
- Geophysics (seismic refraction or reflection, resistivity, etc.).
- Drilling (cored or uncored); a sufficient part of the strata has to be cored to enable laboratory tests to be carried out.
- Logging.
- In-situ geotechnical and/or hydrogeological tests.
- Ground water level measurements/observations.
- Ground water sampling and analyses.
- Laboratory geotechnical and/or hydrogeological and/or geological/petrophysical tests.
- Laboratory compatibility tests involving the product to be stored, and the rock mass.
- Laboratory tests to determine the sensitivity of the cavern wall rock to water.
- Groundwater temperature measurement.

The synthesis of the above data should be used to define the most favorable zones for locating the cavern while taking into account the depth and thickness of the respective potential host layers, the distribution of permeabilities and hydraulic flow patterns, the proximity of possible tectonic zones and, where applicable, such constraints as to insure the independent operation of adjacent caverns dedicated to products of different characteristics.

4.4 Hydraulic Containment

The cavern shall be located deep enough below the groundwater table or relevant piezometric water level to ensure the required hydraulic pressure, and with recharge conditions sufficient to prevent unacceptable depletion of the natural hydrostatic head drainage into the cavern. It might be necessary to enhance the natural hydrogeological flow pattern and/or to provide an artificial water supply by means of water curtains.

4.5 Cavern Stability

Structural stability depends on the geomechanical characteristics of the rock mass. Cavern stability must be ensured for the life of the facility, with almost no possibility of remedial works inside the storage space after the facility start-up.

The design of the caverns (cross sections, pillar widths, crossings, layout) shall ensure the long-term stability of the openings.
The stability of the cavern shall be demonstrated on a theoretical basis by means of adequate numerical simulations (static and dynamic cases), under the maximum allowable operating conditions.

4.6 Maps

Cross-sectional and plan maps for the planned facility should be developed to show the following:
- All wells and other manmade structures and activities within, and for a distance of ¼ mile around the subsurface perimeter of the storage caverns.
- Regional and local faulting.
- The isopach of the host storage formation.
- The hydrogeological conditions surrounding the storage cavern.

4.7 Monitoring Systems

Essential parameter measurements such as cavern pressure at surface and product level shall be measured. Where feasible, this will be done via two independent systems based, if possible, on different physical principles.

The instrument systems shall be specified by means of a detailed review of operation and emergency scenarios, which shall be supported by a process hazard analysis (PHA).

Alarms shall be set on high pressure and, for LPG, on high and low liquid product level in the cavern. These alarms should be generated by the instrument systems. Depending on specific PHA recommendations, these alarms may not be required.

The storage facility shall be equipped with fail-safe devices that operate automatically in case of emergency, unauthorized operation beyond the safe operation of the facility.

The safety principle applied to wellheads and inground completions is that actuated wellhead valves shall automatically close in the event of:
- Failure of the wellhead control panel.
- Site emergency shut-down system actuated either remotely or at the cavity.
- Unauthorized operating conditions at the wellhead or in the cavity.
- Excessive pressure in the cavern.
- Excessive (too high or too low) product level in the cavern.

4.8 Operations

4.8.1 General

All available information on operating histories of local storage facilities should be reviewed to identify the potential for site-specific concerns.
4.8.2 Determination of the Maximum Allowable Operating Pressure

Maximum allowable operating pressure (MAOP) and cavern depth are closely linked by the hydraulic containment principle and well head equipment.

The MAOP of each cavern shall be defined on the basis of:
- The stored product characteristics.
- The future operating conditions.
- The geothermal temperature at cavern depth.
- The overall hydrogeological setting around the caverns (natural or artificially enhanced flow pattern if water curtains are implemented).
- Design parameters of wellhead piping.

In accordance with the hydraulic containment principle outlined in Section 3.4, the cavern must be located at sufficient depth below the water table or relevant piezometric level so that the hydrostatic pressure at the highest point of the cavern is greater than the sum of MAOP plus a safety margin. This cavern depth design principle can be expressed as follows: \( H > MAOP + M \), in which:
- \( H \) is the hydrostatic pressure at the highest point of the cavern (psig).
- MAOP is maximum allowable operating pressure (psig).
- \( M \) is the safety margin (psig).

4.8.3 Maximum Injection and Withdrawal Rates

A study should be completed to determine maximum injection and withdrawal rates. Considerations should include:
- Cavern tightness and stability.
- Equipment, casing and tubing limitations.
5. **DEVELOPMENT AND CONSTRUCTION**

Construction shall be based on adequate procedures.

Contractors shall be well informed on local safety and environmental circumstances and shall be instructed to comply with safety rules and environmental requirements.

The design criteria and options shall be, where applicable, confirmed or adapted during construction to the conditions encountered during excavation.

In particular, the water table shall be permanently monitored by a network of observation wells (piezometers) installed to ensure the integrity of the groundwater table near the caverns.

Construction should follow state-of-the-art procedures.

A reporting system shall be set up, and great care shall be paid to:
- Control of groundwater inflow. Precautions shall be taken to prevent loss of saturation of the surrounding formation, or excessive drop in the water table during construction.
- Adherence to the design shape of the excavation.
- Blasting techniques; when used, they shall be designed to minimize fracturing of the rock around the storage caverns or adjacent formations.
- Induced level of vibration.
- Control of discharge of all wastes, solids and fluids, during excavation. The excavated muck and products used during excavation (e.g. cement admixtures) shall not contaminate groundwater.

When the lines are installed in operation bore holes:
- The bore holes shall be drilled following oil and gas standard practice.
- The casings shall be fabricated, inspected and tested in accordance with standards in force.
- Cement bonding to both casing and strata shall be confirmed by pressure testing to ensure sufficient bonding.

All relevant data concerning cavity construction (records, as-built drawings, quality criteria) should be available to the owner and to the operator of the storage facility.
6. TESTING AND COMMISSIONING

6.1 General

Testing and commissioning shall be based on adequate procedure. Casings and the full cavern volume shall be pressure tested before first filling. Safety devices shall be function-tested prior to operations.

6.2 Product Stored Volume versus Product Level

After construction, the volume of the mined cavern to be used for storage should be measured and plotted as a function of fluid level within the cavern prior to testing. In the case of liquid hydrocarbon storage, a volume versus fluid level (strapping curve) may be prepared on the first fill or a subsequent fill to check the relationship produced by the surveying method.

6.3 Air Pressure Test

6.3.1 Auxiliary Hole Casing Pressure Test

Any cavern auxiliary holes such as pump out wells should be pressure tested with compressed air to a test pressure exceeding the MAOP after casing is cemented.

6.3.2 Main Shaft Casing Pressure Test

In the construction method where one or more main vertical shafts are used as the primary access to the cavern, the shaft(s) and partial cavern volume(s) should be pressure-tested with compressed air to a test pressure equal to or exceeding the MAOP to demonstrate gas tightness. The test should be performed after the main shaft casing(s) have been cemented. The test may be performed after the cement grout is excavated from the bottom of the shaft, prior to any further mining development, or may be performed after a small percentage of cavern volume has been excavated away from the shaft(s) (for example, up to 5,000 barrels). The test pressure should not exceed the hydrostatic pressure at the planned cavern high point (minus an incremental pressure allowed for a safety factor) to avoid jeopardizing the hydraulic containment conditions.

The pressure test length should be sufficient to allow the compressed air to reach pressure/temperature equilibrium plus a time length sufficient to verify either no observable leakage or to measure a quantifiable leak rate.

In the case of an unacceptable leakage rate, the pressure should be released and remedial action taken to correct the leakage before proceeding with further cavern development.
Complete Cavern Pressure Test

After construction, the cavern shall be filled with compressed air, or other available nonflammable gas, to a pressure equal to or exceeding the MAOP to demonstrate gas-tightness. The test pressure should not exceed a level equaling the hydrostatic pressure at the cavern high point (minus an incremental pressure allowed for a safety factor) to avoid jeopardizing the hydraulic containment conditions.

The pressure test length should be sufficient to allow the test gas to reach pressure/temperature equilibrium plus a time length sufficient to verify either no probable leakage or to measure a quantifiable leak rate.

In the case of unacceptable leakage rate, remedial action should be taken to correct the problem prior to placing the cavern in storage service.

6.4 First Filling

The first hydrocarbon filling shall take place only after successful completion of the air pressure test. During the first filling, the vapor space in the caverns shall not be allowed to lead to any explosive mixture with air. Avoidance of an explosive mixture requires either purging the cavern with an inert gas such as nitrogen to reduce oxygen content of the vapor to a level below the explosive limit, or filling first the cavern with water and then displacing it with the product to be stored.

7. MONITORING

7.1 Operating Parameters

The operating pressure of each cavern shall be measured continuously at the wellhead or downhole. In case of pressure measurement at the wellhead, the differential between the wellhead pressure and the pressure in the cavity shall be taken into account by appropriate calculation.

The MAOP should never be exceeded. For LPG, wellhead pressures, product level and water level of each cavern shall be monitored.

7.2 Cavern Stability, Product Containment, Corrosion Monitoring

Monitoring demonstrating cavern stability and successful hydrodynamic containment may be carried out throughout the life of the facility.

The program may include:
- Monitoring of water table levels and/or piezometric ground water levels in bore holes in the vicinity of the caverns, and determination of the hydraulic flow pattern around the caverns.
- Metering of seepage water pumped from the caverns.
• Assessment of cavern stability by seismic monitoring.
• Quality of water from bore holes in the vicinity of the caverns.
• Corrosion monitoring, including periodic casing evaluation surveys.

8. INVENTORY VERIFICATION

All gaseous and/or liquid products injected into or withdrawn from the storage facility shall be metered using industry-accepted standards. The measurements shall be counterchecked by product level measurement in the cavern, (using the level versus volume curve).

The operator of the storage facility shall investigate any losses or gains in inventory and the reasons for the variations. Should the losses be due to migration of the stored hydrocarbon, the operator shall review the integrity of the storage system and the impact, if any, beyond the boundaries of the facility. It would be prudent to shut the facility down if stored hydrocarbons have migrated beyond the facility or out of the cavern. Then the nature of leak must be determined and verified.

9. SURFACE FACILITIES

See clause 1.5 (page 5) regarding compliance with existing regulations on surface facilities. The following items also should be considered in the absence of any applicable regulations:

9.1 Non-Hydrocarbon Storage Field Piping

Non-hydrocarbon storage field piping should be designed in accordance with industry practices. Considerations should include:
• Intended service.
• Temperature variations and potential movement of surface and buried pipe as per ANSI/ASME Standard B31.3.
• MAOP during normal and upset conditions.

9.2 Wellhead Valves

Manual isolation valves should be installed on each wellhead. Each port on the wellhead should be equipped with a valve with a pressure rating that is equal to or greater than the rating corresponding to the maximum cavern pressure. If not, it should be fitted with a blind flange.

9.3 Emergency Shutdown Valves

Mined cavern storage facilities should be equipped with failsafe emergency shutdown (close) valves on all hydrocarbons, or water outlets as applicable.
Emergency shutdown valves should be capable of remote and local operation. Monitoring of valve position should be part of the valve installation. Emergency shutdown valves should be activated automatically by:

- Overpressuring in the hydrocarbon system.
- Underpressuring in the hydrocarbon system.
- Detection of hydrocarbons, heat or flame.

9.4 Monitoring and Venting Tubing and Casing

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

9.5 Design and Construction

Design and construction of non-hydrocarbon storage surface facilities should minimize the possibility of explosion or fire damage to equipment or services necessary for the satisfactory operation of the emergency shutdown system.

9.6 Relief Devices

Operators should consider protecting all piping and valves against thermal expansion of hydrocarbons. All relief devices should be designed according to API RP 520.

9.7 Instrumentation

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

- Flow indicators for hydrocarbon.
- Pressure indicators for cavern hydrocarbons located at the wellhead.

9.8 Wellhead Control Equipment

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

- Failsafe (close) actuators on remote-actuated emergency shutdown valves that are part of the emergency safety system.
- Remote and local manual actuated emergency shutdown controls.
- Automatic actuated emergency shutdown controls.

9.9 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.
10. MATERIALS

See clause 1.5 (page 5) regarding compliance with regulations on materials used in construction. Materials and equipment used to construct underground mined cavern storage systems should be in accordance with the requirements of state and federal regulations.

10.1 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 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.

10.2 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. Attention should be given to past recorded temperature data, the fluid temperature that could occur and the possible effects of extreme air and ground temperatures.

Electrical Classification

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

Qualification of Material

Materials that do not comply with standards or specifications listed here can be qualified for use either by demonstration or technical data to ensure that they are safe.

10.3 Valves, Flanges and Fittings

Steel fittings, flanges and valves should comply with applicable requirements of ANSI, API and ASW, respectively. However, where components made to these standards are not available, it might be permissible to use fittings, flanges and valves made to alternative standards or specifications, provided that equivalency can be demonstrated.
11. OPERATING AND MAINTENANCE PROCEDURES

See clause 1.5 (page 5) regarding compliance with regulations on operating and maintenance procedures. In all cases, operators should have documented procedures in state and federal regulations.

11.1 Emergency Response Procedures

Operators should establish an emergency response plan in compliance with local, state and federal regulations. The plan should include procedures for the safe control or shutdown of the hydrocarbon storage facility in the event of a failure or other emergency. The operator may use periodic drills to ensure performance of operator and emergency response personnel.

11.2 Normal Operating Procedures

Written procedures shall be developed for the following operations of a mined cavern:

- Initial Start-up – Detailed operating procedures shall be developed for new caverns. For caverns already in operation as of January 1, 2000, these procedures need not be developed.
- Normal Shutdown – If the cavern is taken out of service, detailed operating procedures shall be written before it is taken out of service.
- Normal Start-up – If the cavern is taken out of service, detailed operating procedures shall be written before it is placed back in service.
- Normal Operations – Normal operating procedures shall be written to insure safe operations. Normal operating procedures may include normal operations rounds, sampling, logging data, etc.
- Emergency Shutdown – Emergency procedures shall be written to address emergencies identified during the PHA. They shall be in place before a cavern is commissioned.
- Temporary or Special Operations – Any short-term operations to test function or capacity of the cavern shall be written before the operation takes place.

11.3 Abnormal Operating Procedures

Procedures should be developed to safely control depressuring of caverns under all abnormal operating conditions that are likely to be experienced.

11.4 Records

Operators should maintain records and documents of all wellhead and primary safety maintenance and activities for at least 5 years.
11.5 Reviews

Operators should review operating and maintenance procedures annually to ensure that they are consistent with industry and government standards.

11.6 Inspections and Testing of Surface Components

The following components of the facility should be inspected annually:
- Instrumentation, valves, pumps, and emergency equipment.
- Control systems.
- Emergency shut down valves.
- Wellheads and associated pressure monitoring systems.

Test results should be recorded and filed onsite.

11.7 Integrity Testing of Mined Caverns and Casings

Mined caverns and associated casings and wellheads should be tested for integrity prior to commissioning.

11.8 Corrosion Control

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

12. SAFETY

See clause 1.5 (page 5) regarding compliance with existing regulations on safety.

12.1 Fire Prevention and Control

12.1.1 Spacing of Permanent Equipment

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

12.1.2 Control of Combustible Materials

Flare and well sites should be kept free of vegetation and combustible materials at all times.
12.1.3 Buildings

Buildings that contain sources of flammable gas should be constructed in accordance with all applicable state and federal codes and regulations. Where there are no regulations, buildings should be evaluated according to API RP 752.

12.1.4 Flaring

Flaring, where required, should be conducted in the following manner:
- The flare line should terminate with a vertical riser of sufficient height and diameter to prevent flame out and flame lift-off and to 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.
- The flare line and riser should be anchored and provided with an approved means to keep the flame from being extinguished.
- The flare line should be provided with a vessel (vapor knockout vessel) to separate and collect any liquids to prevent the liquids from reaching the flame.
- Vegetation should be removed from the vicinity of the flare stack to a radius of twice the height of the flare stack.

Flare systems should be designed according to API RP 521.

12.2 Staff Training and Certification

12.2.1 Operating Procedure Training

Each employee involved in operating a cavern shall be trained in an overview of operations and procedures. The training shall include emphasis on specific safety and health hazards, emergency operations, including shutdown, and safe practices applicable to the employee’s job tasks.

In lieu of training for employees already involved in operating a process on January 1, 2000, an employer may certify in writing that the employee has the required knowledge, skills and abilities to safely carry out the duties and responsibilities as specified in the operating procedures.

12.2.2 Refresher Training

Refresher training shall be provided at least every three years, and more often if necessary, to each employee involved in operating a cavern to ensure that the employee understands and adheres to the operating procedures. The employer, in consultation with the employees involved in operating the cavern, shall determine the appropriate frequency of refresher training.
12.2.3 Training Documentation

The employer shall ascertain that each employee involved in operating a cavern has received and understood the training required. The employer shall prepare a record which contains the identity of the employee, the date of training and the means used to verify that the employee understood the training.

12.2.4 Wells

While a well is being drilled (or tested during drilling operations), completed, serviced or reconditioned, one person qualified in well control should be onsite and the rig crew should have an understanding of, and be able to operate, the well control equipment.

12.2.5 Storage Operations

Designated representatives of an operator at a storage well or facility should:
- Be qualified to provide competent and effective supervision of the operations.
- Insure that all personnel on the site are informed of the hazards and have knowledge of safety and emergency procedures.
- Insure that all personnel are qualified to operate the facility.

12.2.6 Fire Fighting

Personnel directly involved in the maintenance and operation of underground storage facilities should be trained in fire safety and hazardous materials management.

12.3 Emergency Planning

Operators should develop an emergency plan to deal with accidental hydrocarbon, equipment failures, 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 section 11.1 (page 23), and be subject to annual auditing.

12.4 Security

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

Barricades should be placed to prevent vehicular collision with the wellhead. If the facility is unattended, the operator may consider additional surveillance capabilities (e.g. caverns) and a minimum response time by operations personnel (e.g. 30 minutes).
12.5 Escape

Fences that surround wells at mined cavern storage facilities should have at least two gates conveniently located to provide separate escape routes.

12.6 Identification Signs

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

12.7 Warning Signs

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

12.8 Voice Communication

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

12.9 Process Hazard Analysis

The employer shall perform an initial process hazard analysis (PHA) on the cavern installation. The PHA shall be appropriate to the complexity of the cavern installation and shall identify, evaluate and control the potential hazards in the installation.

The employer shall use one or more of the following methodologies appropriate to determine and evaluate the hazards:
- What-If
- Checklist
- What-If/Checklist
- Hazard and Operability Study (HAZOP)
- Failure Mode and Effects Analysis (FMEA)
- Fault Tree Analysis
- Appropriate equivalent methodology

The process hazard analysis shall address:
- Hazards of the cavern.
- Identification of any previous incident which had a potential for catastrophic consequences.
- Engineering and administrative controls applicable to the hazards and their interrelationships such as appropriate application of detection methodologies to provide early warning of releases. (Acceptable detection methods might include process monitoring and control instrumentation with alarms, and detection hardware such as hydrocarbon sensors.).
• Consequences of failure of engineering and administrative controls.
• Facility siting.
• Human factors.
• A qualitative evaluation of a range of possible safety and health effects on employees of failure of controls.

The PHA shall be performed by a team with expertise in engineering and cavern operations. Also, one member of the team must be knowledgeable in the specific PHA methodology being used.

The employer shall establish a system to promptly address the team's findings and recommendations; assure that the recommendations are resolved in a timely manner and that the resolution is documented; document what actions are to be taken; complete actions as soon as possible; develop a written schedule of when these actions are to be completed; communicate the actions to operating, maintenance and other employees whose work assignments are in the cavern and who may be affected by the recommendations or actions.

After completion of the initial cavern PHA, the PHA shall be updated and revalidated at least every 5 years by a team meeting the requirements above to ensure that the process hazard analysis is consistent.

Employers shall retain for the life of the cavern PHAs and updates or revalidations for each installation, as well as the documented resolution of recommendations described above.

12.10 Management of Change / Pre-Start-up Safety Review

Managing changes to the facilities are important to prevent catastrophic failure of the cavern and insure that the installation maintains safe operation.

12.10.1 Management of Change

The employer shall establish and implement written procedures to manage changes (except for "replacements in kind") to facilities, material stored, technology, equipment and procedures that affect the cavern.

The procedures shall ensure that the following considerations are addressed prior to any change:
• The technical basis for the proposed change.
• A hazard review that includes the impact of change on safety and health (PHA methods may be used for the hazard review).
• Modifications to operating procedures.
• Necessary time period for the change.
• Authorization requirements for the proposed change.
Employees who operate a cavern, and maintenance and contract employees whose tasks will be affected by a change shall be informed of, and trained for, the change before it is made.

If a change covered by this section results in a change in the process safety information required by section 12.11, such information shall be updated accordingly.

If a change covered by this paragraph results in a change in the operating procedures or practices required by section 11.2, such procedures or practices shall be updated accordingly.

12.10.2 Pre-Start-up Safety Review

The employer shall perform a pre-start-up safety review for new and modified facilities when the modification is significant enough to require a change in the process safety information.

The pre-start-up safety review shall confirm that prior to the introduction of hydrocarbons into the change:
- Construction and equipment is in compliance with design specifications.
- Adequate safety, operating, maintenance and emergency procedures are in place.
- All recommendations of the hazard review in the management of change phase have been resolved or implemented before start-up.
- Training of employees involved in operating a process has been completed.

12.11 Process Safety Information

The employer shall compile written process safety information before conducting any PHA. The written process safety information is to enable the employer and the employees to identify and understand the hazards posed by cavern installation. This process safety information shall include information pertaining to the hazards of the material stored, the technology of the cavern construction and the cavern equipment.

12.12 Incident Investigation

The employer shall investigate all incidents that result in, or could reasonably have resulted in, an uncontrolled release of stored hydrocarbons or other problem that increases the potential for an uncontrolled release.

An incident investigation shall be initiated as promptly as possible, but not later than 48 hours after the incident.

An incident investigation team shall consist of at least one person knowledgeable in the cavern operations and other people with appropriate knowledge and experience to thoroughly investigate and analyze the incident.
At the conclusion of the investigation, a written report shall be prepared that includes at a minimum:
- Date of incident.
- Date investigation began.
- A description of the incident.
- Factors that contributed to the incident.
- Any recommendations resulting from the investigation.

The employer shall establish a system to promptly address and resolve the incident report findings and recommendations. Resolutions and corrective actions shall be documented.

The report shall be reviewed with all affected personnel whose jobs are relevant to the incident findings.

Incident investigation reports shall be retained for five years. Any documents or records that contain information pertinent to the resolution of any pending regulatory enforcement proceeding shall be retained beyond the five-year period until the resolution of such proceedings.

13. ABANDONMENT AND SITE RESTORATION

See clause 1.5 (page 5) regarding compliance with regulations on well abandonment.

13.1 Cavern Abandonment

13.1.1 Hydrocarbon Evacuation

Prior to abandonment, the cavern should be evacuated, to the extent practicable, of all hydrocarbons by pumping out the contents and allowing complete water filling. The rock structure’s integrity should be evaluated for its reaction to water before filling the cavern with water.

13.2 Abandonment

13.2.1 Abandonment Design

A well abandonment design should insure that the storage zone is isolated from all other porous or hydrocarbon-bearing horizons, and from the surface.

13.2.2 Removal of Downhole Equipment

All downhole equipment and uncemented casing or tubing strings should be removed from the wellbore prior to starting abandonment operations unless circumstances prohibit their removal.
13.2.3 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 above and within 20 feet of the cavern roof. The sealing unit should then be capped with a minimum of 25 feet of cement. Where practical, the entire wellbore may be filled with cement.

13.2.4 Wellbore Fluid

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

13.2.5 Additional Plugs

If the entire wellbore is not to be plugged, then 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.

13.3 Surface Abandonment

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

13.4 Surface Restoration

Surface restoration should return the surface to its original condition or as nearly as possible to its original condition.
Additional Issues To Be Considered In Framing State Regulations

- Is such storage geologically feasible?
- Are suitable rock formations 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 be responsible for drafting necessary legislation, and for oversight?
- What is the proper compliance schedule?
- When should it apply to new hydrocarbon caverns?
- When should it apply to existing caverns?
- When should it apply to existing mines being modified to hydrocarbon storage?
- Should projects be reviewed administratively, at public hearings, or both?
  1. Requirements
  2. Notice
- What is the appropriate geological area for impact review?
- What things should be considered?
- To what extent 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?
  1. By the applicant
  2. By the state agency with oversight
- What warning systems, alarms, training and emergency response systems will be required?
  1. Of the applicant
  2. Of the state, or other agencies
- What is the procedure for granting exceptions to policy?
  1. On the basis of extraordinary commercial merit
  2. 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?
- What cross-checks and inspections are to be performed during operation, and at which frequency, to verify the compliance with the safety standards and the perfect containment?
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 mined cavern facilities. In all cases the latest edition should be used.

American National Standards Institute/American Society of Mechanical Engineers (ANSI/ASME) Standards
B31.3 Piping in Chemical Plants and Petroleum Refineries
B36.10M Nominal Piping Size
B 16.5 Pipe Flanges and Fittings
B 16.9 Factory-Made Wrought Field Butt Welding Fittings
B31.4 Liquid Transportation Systems for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia, and Alcohols

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 1--Design
Part 11--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 5B 1 Recommended Practice for Gaging and Inspection of Casing, Tubing and Pipe Line Threads
RP 5C 1 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-1A Nondestructive Testing Personnel Qualification and Certification

American Society for Testing and Materials Standards
E 142-86 Method for Controlling Quality of Radiographic Testing

American Welding Society Standard

Compressed Gas Association Publications
National Association of Corrosion Engineers
MR-01-75 Sulfide 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
APPENDIX C. IOGCC MEMBER STATE CONTACTS

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State Oil & Gas Board
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Tuscaloosa, AL 35486-9780
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Louisiana
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P.O. Box 94275
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