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# Geological Storage: Underground Gas Storage

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***Summary***

*Underground reservoirs (depleted gas reservoirs, aquifer reservoirs and salt cavern reservoirs ) are most important type of underground natural gas storage. Characteristics of underground storage facilities need to be defined and measured: Total gas storage capacity, Total gas in storage, Base gas (also referred to as cushion gas), Working gas capacity, Working gas, Physically unrecoverable gas, Cycling rate, Deliverability, and Injection capacity (or rate). Underground natural gas storage is relied upon to smooth the natural gas supply to feed high peak gas demands. The key to smoothing the supply is to be able to store during periods of low demand large quantities of gas that can be produced quickly to meet peak demand. Surplus natural gas (methane) delivered by pipelines to consuming areas is injected into large underground reservoirs. The most important characteristic of an underground storage reservoir is its capability to hold natural gas for future delivery. The measure of this is called working gas capacity: the amount of natural gas inventory that can be withdrawn to serve customer needs. In addition to working (top storage) gas, underground storage reservoirs also contain base (cushion) gas and, in the case of depleted oil and/or gas field reservoirs, native gas. Native gas is the gas that remains after economic production ceases and before conversion to use as a storage site. Upon development of a storage site, additional gas is injected and combined with any existing native gas in order to develop and maintain adequate storage reservoir pressure to meet required service. The resulting (permanent) inventory is referred to as the base or cushion load. During heavy demand periods, some base gas may be withdrawn temporarily and delivered as working gas, but over the long term, base levels must be maintained to ensure operational capability.*

**Introduction**

Depleted reservoirs are also attractive because their geological and physical characteristics have already been studied by geologists and petroleum engineers and are usually well known. Consequently, depleted reservoirs are generally the cheapest and easiest to develop, operate, and maintain of the three types of underground sto rage. Geologically, it is preferred that depleted reservoir formations have high porosity and permeability . The porosity of the formation is one of the factors that determines the amount of natural gas the reservoir is able to hold. Permeability is a measure of the rate at which natural gas flows through the formation and ultimately determines the rate of injection and withdrawal of gas from storage.

Carbon Dioxide for Enhanced Gas Recovery and As Cushion Gas : Natural gas Reservoirs are obvious targets for carbon sequestration by direct carbon dioxide ($CO_2$ ) injection , because of their proven record of gas production and integrity against gas escape. Carbon sequestration in depleted natural gas reservoirs can be coupled with enhanced gas production by injecting $CO_2$ into the reservoir as it is being produced, a process called Carbon Sequestration with Enhanced Gas Recovery (CSEGR). In this process, supercritical $CO_2$ is injected deep in the reservoir while methane ($CH_4$) is produced at wells some distance away. The active injection of $CO_2$ causes rep ressurization and $CH_4$ displacement to allow the acceleration and enhancement of gas recovery relative to water -drive or depletion-drive reservoir operations. Carbon dioxide undergoes a large change in density as $CO_2$ gas passes through the critical pressure at temperatures near the critical temperature . This feature makes $CO_2$ a potentially effective cushion gas for gas storage reservoirs. Thus at the end of the CSEGR process when the reservoir is filled with $CO_2$, additional benefit of the reservoir may be obtained through its operation as a natural gas storage reservoir.

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Aquifers (underground, porous and permeable rock formations ) are the least desirable and most expensive type of natural gas storage facility for a number of reasons. First, the geological characteristics of aquifer formations are not as thoroughly known, as with depleted reservoirs. In addition to these considerations, aquifer formations typically require a great deal more 'cushion gas' than do depleted reservoirs.

Underground salt formations are well suited to natural gas storage. Salt caverns allow very little of the injected natural gas to escape from storage unless specifically extracted.

The walls of a salt cavern are strong and impervious to gas over the lifespan of the storage facility. Salt caverns provide very high withdrawal and injection rates relative to their working gas capacity Gas storage is principally used to meet seasonal load variations. Gas is injected into storage during periods of low demand and withdrawn from storage during periods of peak demand. It is also used for a variety of secondary purposes, including: Balancing the flow in pipeline systems, Maintaining contractual balance, Leveling production over periods of fluctuating demand, Insuring against any Natural Calamities, Meeting regulatory obligations, Reducing price volatility,and Offsetting changes in natural gas demands Terminology used in UGS - Characteristics of underground storage facilities need to be defined and measured. A number of volumetric measures have been put in place for that purpose: Total gas storage capacity: It is the maximum volume of natural gas that can be stored at the storage facility. It is determined by several physical factors such as the reservoir volume, and also on the operating procedures and engineering methods used. Total gas in storage: It is the total volume of gas in storage at the facility at a particular time. Working gas capacity: It is the total gas storage capacity minus the base gas. Working gas: It is the total gas in storage minus the base gas. Working gas is the volume of gas available to the market place at a particular time. Physically unrecoverable gas: The amount of gas that becomes permanently embedded in the formation of the storage facility and that can never be extracted. Cycling rate: It is the average number of times a reservoir's working gas volume can be turned over during a specific period of time. Typically the period of time used is one year.

Deliverability: It is a measure of the amount of gas that can be delivered (withdrawn) from a storage facility on a daily basis. It is also referred to as the deliverability rate, withdrawal rate, or withdrawal capacity and is usually expressed in terms of millions of cubic feet of gas per day (MMcf/day) that can be delivered.

Injection capacity (or rate): It is the amount of gas that can be injected into a storage facility on a daily basis. It can be thought of as the complement of the deliverability. Injection rate is also typically measured in millions of cubic feet of gas that can be delivered per day (MMcf/day).

Base gas (also referred to as cushion gas): It is the volume of gas that is intended as permanent inventory in a storage reservoir to maintain adequate pressure and deliverability rates throughout the withdrawal season.

The measurements above are not fixed for a given storage facility. For example, deliverability depends on several factors including the amount of gas in the reservoir and the pressure etc. Generally, a storage facility's deliverability rate varies directly with the total amount of gas in the reservoir. It is at its highest when the reservoir is full and declines as gas is withdrawn. The injection capacity of a storage facility is also variable and depends on factors similar to those that affect deliverability. The injection rate varies inversely with the total amount of gas in storage. It is at its highest when the reservoir is nearly empty and declines as more gas is injected. The storage facility operator may also change operational parameters. This would allow, for example, the storage capacity maximum to be increased, the withdrawal of base gas during very high demand or reclassifying base gas to working gas if technological advances or engineering procedures allow.

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## Theory/Method:

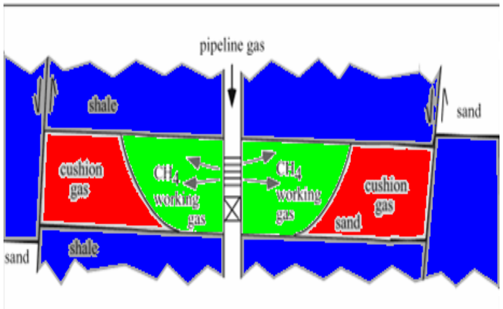


Fig.(1): Idealized single-well natural gas storage schematic showing working gas and cushion gas. Figure source: *Energy & Fuels* **2003,** *17,* 240-246(esd.lbl.gov)

### Methods of Underground Storage of Natural Gas

The most important type of gas storage in underground reservoirs are depleted gas reservoirs, aquifer reservoirs , salt cavern reservoirs ,mined caverns(hard rock) and abandoned mines [1].

### Depleted oil & Gas Reservoirs

Depleted reservoirs are attractive because their geological and physical characteristics have already been investigated by geoscientists are usually well known Oil and gas fields that have already been more or less fully exploited are particularly suitable for the underground storage of natural gas. As these structures have successfully kept their hydrocarbon deposits trapped for millions of years, they have already demonstrated their geological suitability for storage purposes. No special exploration is required for this kind of storage and, as an additional advantage, any existing exploitation wells can potentially be re-used for gas injection and gas withdrawal The gas stored in this type of facility is injected under a pressure that is higher than the actual reservoir pressure - so that, when there is an increase in demand for gas, it can be withdrawn by expansion.

The gas turnover rates that can be achieved from such reservoirs are dependent on the dimensions and design of the original exploitation wells and on the properties of the reservoir. To increase gas turnover rates, especially in thin rock layers, new wells are increasingly being drilled in such a way that the lower section of the well runs horizontally along the storage formation. This provides a considerably larger flow area for the gas along with significantly higher injection and withdrawal rates. When depleted fields are used for natural gas storage, the possibility of any residual gases mixing with the injected gas cannot be excluded. Measures for avoiding quality problems (e.g. by increasing the cushion gas volume of storage gas) may have to be considered, depending on the differences in composition of any residual gas and the storage gas. This is also why gas processing plants are sometimes installed at the surface to guarantee that the gas re-injected into the pipeline has the same quality as the pipeline gas. Geologically, it is preferred that depleted reservoir formations have high porosity and permeability. The porosity of the formation is one of the factors that determines the amount of natural gas the reservoir is able to hold. Permeability is a measure of the rate at which natural gas flows through the formation and ultimately determines the rate of injection and withdrawal of gas from storage.

Operators of CO2 sequestration facilities will need to address issues similar to those faced by the gas storage industry, including: migration of injected gas over extended periods of time; reliable monitoring of gas location; and monitoring of zones above cap rocks for evidence of gas leakage.

Technologies used in the underground gas storage industry and evaluated their applicability to CO2 sequestration. The storage of natural gas in high-permeability aquifers under structural conditions that mimic naturally occurring oil and gas reservoirs (Fig.3). The technologies developed to ensure the reliability of aquifer-based gas storage also may be useful for CO2 sequestration.

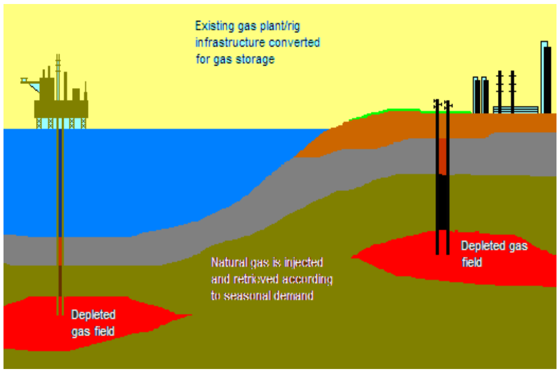


Fig. (2 ) left : Depleted offshore field ,right-Depleted onshore field(Figure source : undergroundgasstorage.com)

Site selection plays a major role in preventing leakage, with particular attention to caprock integrity. Caprock leakage of stored gas is less likely from depleted fields than from aquifers, where naturally occurring oil or gas has not challenged sealing capability and integrity. It also is important to note that CO2 storage and natural gas storage havedifferent operational requirements. Natural gas storage requires "steep" structural closure to ensure gas deliverability, but this same feature increases the likelihood of caprock flaws. Because sequestered CO2 is not intended to be withdrawn from storage, this type of structure offers no advantage and should be avoided.

Although the demands placed on sites intended to temporarily store natural gas differ from those meant to permanently sequester CO2, it is clear the gas storage industry can provide valuable insights into many of the challenges associated with underground CO2 storage.

**Aquifer Reservoir**

Aquifers[1,2] are underground, porous and permeable rock formations that act as natural water reservoirs. Aquifers are the least desirable and most expensive type of natural gas storage facility for a number of reasons. First, the geological characteristics of aquifer formations are not as thoroughly known, as with depleted reservoirs. A significant amount of time and money goes into discovering the geological characteristics of an aquifer, and determining its suitability as a natural gas storage facility. Seismic testing must be performed, much like is done for the exploration of potential natural gas formations. The area of the formation, the composition and porosity of the formation itself, and the existing formation pressure must all be discovered prior to development of the formation. In addition, the capacity of the reservoir is unknown, and may only be determined once the formation is further developed.

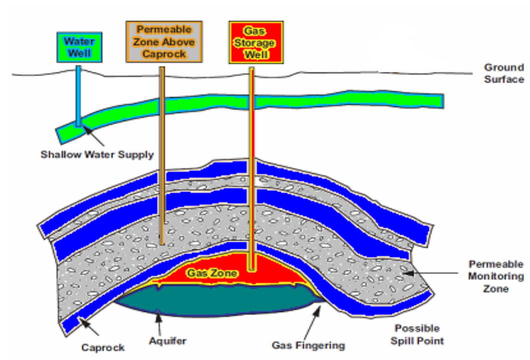


Fig.(3):(natural**gas**.org);Natural gas storage in high-permeability aquifers that have the same naturally ocurring oil and gas reservoirs.

Aquifer formations typically require a great deal more 'cushion gas' than do depleted reservoirs. Since there is no naturally occurring gas in the formation to begin with, a certain amount of natural gas that is injected will ultimately prove physically unrecoverable. In aquifer formations, cushion gas requirements can be as high as 80 percent of the total gas volume. While it is possible to extract cushion gas from depleted reservoirs, doing so from aquifer formations could have negative effects, including formation damage. As such, most of the cushion gas that is injected into any one aquifer formation may remain unrecoverable, even after the storage facility is shut down.

Aquifer structures require large expenditures for the exploration of the geological conditions and the initial operation phase. The monitoring of the gas-water interface and tightness during long-term operation can be compared to that of depleted oil or gas fields. Nevertheless, aquifer structures sometimes present the only geological opportunity to establish an underground storage facility at an acceptable distance from the gas pipeline system. This particular type of underground storage has only small impact on the environment since its operation requires neither freshwater injection nor the disposal of brine. Depending on their storage characteristics, aquifer structures serve mainly for the seasonal balancing of natural gas supply and for peak shaving.

**Salt Caverns for Gas Storage**

Salt caverns are typically much smaller than depleted gas reservoirs and aquifers. However, deliverability from salt caverns is typically much higher than for either aquifers or depleted reservoirs. Therefore natural gas stored in a salt cavern may be more readily (and quickly) withdrawn, and caverns may be replenished with natural gas more quickly than in either of the other types of storage facilities. Moreover, salt caverns can readily begin flowing gas on as little as one hour's notice, which is useful in emergency situations or during unexpected short term demand surges. Salt caverns may also be replenished more quickly than other types of underground storage facilities.

Underground salt formations are well suited to natural gas storage in that salt caverns, once formed, allow little injected natural gas to escape from the formation unless specifically extracted. The walls of a salt cavern are strong and impervious to gas over the lifespan of the storage facility.

Essentially, salt caverns are formed out of existing salt deposits. These underground salt deposits may exist in two possible forms: salt domes, and salt beds. Salt domes are thick formations created from natural salt deposits that, over time, leach up through overlying sedimentary layers to form large dome-type structures. They can be as large as a mile in diameter, and 30,000 feet in height. Typically, salt domes used for natural gas storage are between 6,000 and 1,500 feet beneath the surface, although in certain circumstances they can come much closer to the surface. Salt beds are shallower, thinner formations. These formations are usually no more than 1,000 feet in height. Because salt beds are wide, thin formations, once a salt cavern is introduced, they are more prone to deterioration, and may also be more expensive to develop than salt domes.

Once a suitable salt dome or salt bed deposit is discovered, and deemed suitable for natural gas storage, it is necessary to develop a 'salt cavern' within the formation. Essentially, this consists of using water to dissolve and extract a certain amount of salt from the deposit, leaving a large empty space in the formation. This is done by drilling a well down into the formation, and cycling large amounts of water through the completed well. This water will dissolve some of the salt in the deposit, and be cycled back up the well, leaving a large empty space that the salt used to occupy. This process is known as 'salt cavern leaching'.

Salt cavern leaching is used to create caverns in both types of salt deposits, and can be quite expensive. However, once created, a salt cavern offers an underground natural gas storage vessel with very high deliverability. In addition, cushion gas requirements are the lowest of all three storage types, with salt caverns only requiring about 33 percent of total gas capacity to be used as cushion gas.

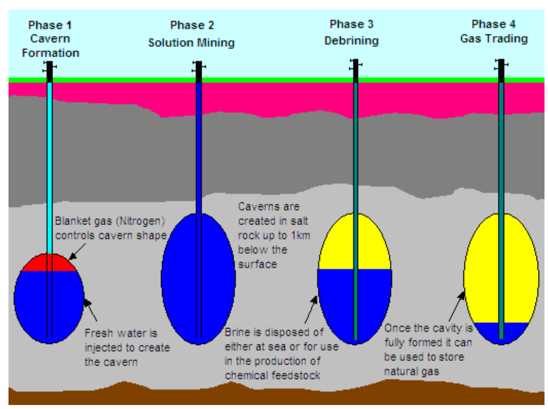


Fig.(4):Underground gas storage in Salt Cavern (Figure source: undergroundgasstorage.com)

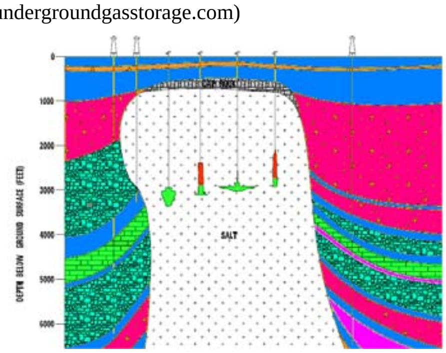

Fig.(5): (Figure source, enerkon.com); Underground gas storage in Salt Cavern

As salt caverns are open vessels they offer very high deliverability, with high flow rates meaning this type of storage facility is best used for short term trading.Solution mining under Gas (SMUG) Before the leaching process comes to the end, the upper part of the cavern can already be used for gas storage operation. Lined Rock Cavern (LRC) Technology is to provide storage capacities for countries where the lack of suitable geological formations does not allow any other form of ground storage facility[7]. Mined Caverns : In those locations where neither salt caverns can be leached nor suitable aquifer structures or depleted oil or gas fields are available, there may be the right geological conditions for the construction of caverns in hard rock by traditional mining techniques. This type of storage is especially suitable for products that are in a liquid state under atmospheric conditions.

Dissused Mines : Mines that are no longer used for mineral extraction can be suitable for underground storage if the surrounding rock formation is geologically tight and existing shafts and boreholes can be safely and economically plugged.

**Geosciences, Gas storage geomechanics and reservoir engineering**

For depleted reservoirs, geological information is usually available from the original oil and gas exploration process (although both borehole logging and geophysical investigations tend to focus on the reservoir horizons and further data might need to be obtained on the overburden strata). The assessment needs to take account of reservoir properties (dimensional and geomechanical) to avoid over-filling and over-pressuring, well design to avoid system leaks, and overburden geology to identify potential migration pathways. Rock-salt (halite) is a very low-permeability material and has self-annealing properties. Both characteristics making it eminently suitable for gas storage and its high-water solubility makes it readily amenable to solution mining. Salt beds appropriate for cavern development need to be thick enough to accommodate suitably shaped caverns with a capacity of about 1 million cubic meters and sufficiently deep to contain gas under high pressures without fracturing. Regional geological information and seismic surveys can identify beds with the right geometry, but salt is not the same everywhere.

Therefore, thorough geotechnical investigation is also necessary to ensure that the formation is compatible with the required storage pressures and other operational parameters. As with depleted reservoirs, injection/withdrawal well design and overburden geology are important in assessing gas escape and migration potential. Maximum safe operating pressure for a gas storage reservoir depend on three primary geomechanical factors. These are : The mechanical properties of the reservoir and overburden; The natural state of stress in the reservoir and overburden; The stress changes induced in the reservoir and overburden by gas pressure cycling. Different design parameters are varied to determine the influence on the accumulation of damage in salt and on the deformation of the salt cavern. These are the lower limit of the cavern pressure, the cavern pressure history, operational conditions, and cavern size expressed in terms of height/diameter(H/D) ratio, overburden stiffness, interface properties and roof thickness.

**Conclusions**

There are basically two uses for natural gas in storage facilities: meeting base load requirements, and meeting peak load requirements. Natural gas storage is required for two reasons: meeting seasonal demand requirements, and as insurance against unforeseen supply disruptions. Base load storage capacity is used to meet seasonal demand increases. Base load facilities are capable of holding enough natural gas to satisfy long term seasonal demand requirements. These reservoirs are larger, but their delivery rates are relatively low, meaning the natural gas that can be extracted each day is limited. Instead, these facilities provide a prolonged, steady supply of natural gas. Depleted gas reservoirs are the most common type of base load storage facility. Peak load storage facilities, on the other hand, are designed to have high-deliverability for short periods of time, meaning natural gas can be withdrawn from storage quickly should the need arise. Peak load facilities are intended to meet sudden, short-term demand increases. These facilities cannot hold as much natural gas as base load facilities; however, they can deliver smaller amounts of gas more quickly, and can also be replenished in a shorter amount of time than base load facilities. While base load facilities have long term injection and withdrawal seasons, turning over the natural gas in the facility about once per year, peak load facilities can have turn over rates as short as a few days or weeks. Salt caverns are the most common type of peak load storage facility, although aquifers may be used to meet these demands as well. The displacement of both gas components involves convective and dispersive transport mechanisms. Convection, conventionally described by Darcy's law, does not lead to mixing. Dispersive transport is governed by diffusion and dispersion. Whereas diffusion is the result of random motion of gas molecules, the term dispersion is used to cover a variety of physical phenomena.

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