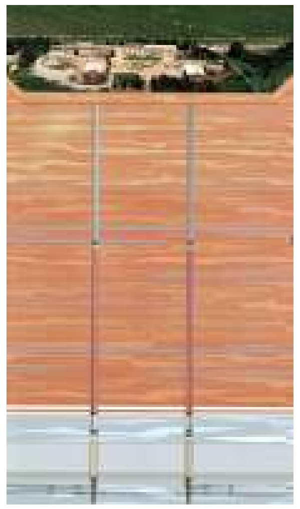
If required the gas can be withdrawn by expansion due to the internal gas overpressure. But before regular gas storage operation can be practised the cavern must be discharged from the brine. A tubing installed in the well and reaching down to the cavern bottom forms an annulus through which the gas can be injected while simultaneously the equivalent amount of brine is withdrawn through that tubing.

When storing liquid products, the liquid injected through the annulus replaces the brine in the cavern via the brine withdrawal string. For product discharge the same process in the opposite direction takes place. If unsaturated brine is used for product withdrawal the turnover is accompanied by an increase in cavern volume due to further salt dissolution.

Disused mines (4)

Mines not used any more 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. But the technological difficulties and obstacles for achieving such level of tightness should not be disregarded.

As disused mines are mostly operated at a low pressure level within a small pressure range the installation of additional compression capacity is normally not necessary. In such case the gas is injected if the pipeline pressure exceeds the pressure in the mine and – vice versa - the gas is discharged if the pressure in the pipeline drops considerably down.



Disused mines are favourable for storing natural gas underground without using compressors. The varying pipeline pressure allows for applying the "respiratory exchange technology".

That way of storing natural gas without compressors is called "respiratory exchange technology".

Although the gas pressure range is quite small, large working gas quantities can be achieved due to the enormous volume of the galleries and chambers already mined and storage operation at low cost can be practised.

Mined rock caverns (5)

At locations where neither salt caverns can be solution mined nor suitable aquifer structures or depleted hydrocarbon fields are available, the geological conditions for the construction of caverns in hard rock by traditional mining technologies might exist. That type of storage is especially suitable for those products which are under atmospheric conditions in the liquid state. But also liquefied gases can be stored in that way cost-effectively. The rock material excavated is removed either through a vertical shaft or by dumpers through a tunnel. Once the storage caverns and connecting galleries are completed the shaft or the tunnel will be plugged by cement. Storage volumes of several 100,000 cbm can be achieved. Tubulars installed in a vertical shaft are used for product injection and discharge. The shaft itself is separated from the storage cavern by a cemented plug. For product discharge submersible pumps are applied.

To prevent the stored product from penetration into the fissures of the surrounding rock a water curtain is created enveloping the cavity and ensuring its tightness. The stability of the hard rock caverns is proven in advance by geomechanical calculations.

Surface facilities are necessary for the separation of water from the product stored, for metering and for loading and unloading operations (road tankers, rail tank-wagon, ships and pipelines).

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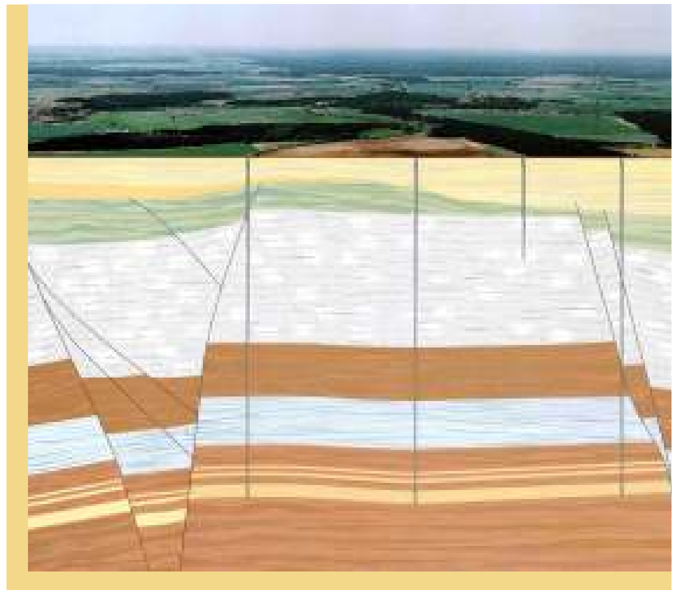
A Short Introduction to Underground Storage



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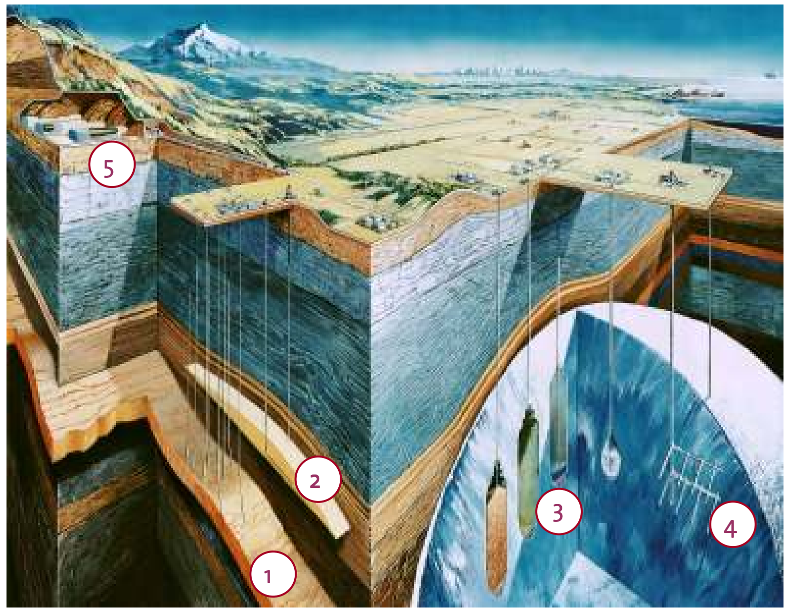
What is underground Storage about?

Underground storage is the safe, economic and environmentally friendly way of storing large volumes of hydrocarbons, energy sources, chemical products etc. under liquid, liquefied or gaseous form in porous or fractured rocks or man made cavities hosted in geological formation deep below ground surface level.

Underground storage facilities serve for seasonal balancing between summer and winter time, for peak-shaving when the demand is extremely high, as emergency supply if the pipeline system failed and as strategic reserve for managing serious crisis in supply. But they are also increasingly used for spot-trading.

Typical products stored are natural gas, crude oil, air, fuels, propane/butane, chemical and petrochemical products. The volumes stored are huge. In the case of natural gas they can reach several hundred millions cbm up to some billion cbm. The withdrawal capacity of a storage site exceeds normally hundred thousands cbm/hr and can reach even several millions cbm/hr. Underground storage of gaseous products takes place under high pressure ranging from several dozens bar to even more than 200 bar.

Depleted hydrocarbon fields (1), aquifer structures with a tight overburden (2), solution mined caverns in rock salt (3), disused mines (4) or traditionally mined hard rock cavities (5) are used for underground storage.



Graphic by Günter Radtke, by courtesy of KBB UT Hannover

Consequently underground storage is depending on the existence of suitable geological conditions.

Depleted oil & gas fields (1)

Hydrocarbon reservoirs already exploited to a certain extend are in principle suitable for underground storage of natural gas. Since these structures had kept the hydrocarbons for millions of years successfully trapped they demonstrated their geological suitability for storage purposes. For that storage technique no special exploration is required. And, what is an additional advantage, the existing exploitation wells can potentially be re-used for gas injection and gas withdrawal.

The gas to be stored is injected with a pressure higher than the actual reservoir pressure. When the gas demand increases the gas is withdrawn by expansion. The achievable turnover rates are mainly limited by the dimension and design of the storage wells and by the reservoir properties. In order to overcome these limitations especially in thin rock layers new storage wells are increasingly drilled in such a way that the lower section of the well runs horizontally in the storage formation. This provides for the gas a considerably larger flow area and yields significantly higher injection and withdrawal rates.

When using depleted fields for natural gas storage a more or less intense mixing of the residual gas with the injected gas cannot be excluded. Depending on the differences in the gas composition of the residual and the storage gas and on the mixing processes measures have to be considered in order to avoid quality problems (e.g. by increasing the cushion gas volume for the storage gas; hydrocarbon/liquid separation in case of depleted oil fields; ...). This is why apparently gas processing plants have to be installed at the surface, which guaranty that the gas re-injected to the gas pipeline grid meets the quality requirements (separation of liquid hydrocarbon fractions or detrimental gas components). Depending on their storage characteristics depleted fields serve mainly for seasonal balancing of natural gas as well as for peak shaving.

Aquifer structures (2)

Porous or fractured geological formation filled with mineralized water can turn out to be applicable for underground storage, if its shape forms a structural trap (e.g. anticline) and if covered by a geologically tight overburden.

If the suitability of such structure has been proven by adequate geological and geophysical exploration methods, boreholes are to be drilled to the top of that structure and cased. Through these wells natural gas is injected under high pressure. Due to its low specific gravity the compressed gas accumulates in the top of the aquifer structure and creates a zone of high gas saturation. Filling all spaces it displaces the mineralized water to lower and far distant regions of the aquifer structure. When

natural gas is withdrawn the pressure in the gas-filled pores reduces and the mineralized water flows partly back. The movement of the gas water contact can be monitored and predicted by reservoir engineering methods avoiding an inadmissible backflow of water into the storage reservoir.

The productivity of the storage wells in an aquifer structure is occasionally restricted by the rock properties and the thickness of the target formation. In order to overcome such limitations especially in thin layers the boreholes are increasingly drilled horizontally in their lower part. By this mean a far larger well productivity can be achieved.

Aquifer structures are characterized by high expenditures for the exploration of the geological conditions and the initial phase of operation. The monitoring of the gas-water-interface and the tightness during long term operation is comparable to depleted hydrocarbon fields. But aquifer structures are sometimes the only geological opportunity for establishing an underground storage facility in an acceptable distance to the gas pipeline system. This technique of underground storage has solely a little impact on the biosphere because for the operation of aquifer structures, neither fresh water is necessary nor brine has to be disposed off.

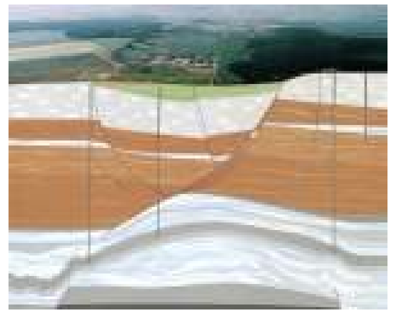
Depending on their storage characteristics aquifer structures serve mainly for seasonal balancing of natural gas as well as for peak shaving.

Salt caverns (3)

Under certain conditions salt rock can appear in the subsurface with considerable thickness as bedded salt or as salt domes. If the salt is of sufficient thickness caverns can be established suitable for storage purposes. Salt caverns are large cavities artificially created by solution mining. In order to create such a cavern by leaching it is necessary to drill and to case a borehole up to the depth of the salt formation. Through that borehole water is injected which will dissolve the salt. The brine produced in that way is withdrawn to the surface by another string concentrically installed in the well. In that way caverns up to a volume of several 100,000 cbm can be created. During cavern leaching and the latter storage operation the cavern shape is periodically monitored by sonar surveys. The stability of the caverns is proved by geomechanical investigations.

Salt caverns are suitable for storing gas under high pressure (preferably natural gas) as well as liquids inert to both water and salt (e.g. crude oil, oil products, fuels, propane/butane). The tightness of salt caverns results from the plastic creep behaviour of the salt rock. Salt caverns allow for extremely high withdrawal rates and are therefore specific for peak-shaving purposes.

In order to create a cavern volume of 1 mffi an average amount of 8 mffi freshwater has to be injected and to be withdrawn as brine. From that ratio arises one of the major problems solution mining is confronted with: How to deal with the enormous quantities of the brine produced? Provided that inland is no opportunity for brine processing (salt production or chemical industry) an environmentally friendly alternative is given by injection of the brine into deep porous or fractured rocks already filled with mineralised water and covered with a tight overburden. For gas storage purposes the gas has to be injected into the cavern with a sufficient pressure.



In depleted gas or oil fields the gas is stored under high pressure in the pores or fractures of the storage reservoirs.

The major advantage of salt caverns for gas storage is their very high gas withdrawal capacity.