# COMPRESSED AIR ENERGY STORAGE: MATCHING THE EARTH TO THE TURBO-MACHINERY- NO SMALL TASK

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Compressed Air Energy Storage (CAES) is a process for storing and delivering energy as electricity. A CAES facility consists of an electric generation system and an energy storage system. Only earth based geological structures can currently store adequate potential energy in the form of a pressurized air mass required by commercial electric turbines. Earth based structures suitable for service as air storage vessels include 1) solution mined salt cavities, 2) excavated mine cavities, 3) aquifer-water bearing geologic structures, and 4) depleted natural gas reservoirs. *Hydrodynamics* has found that the greatest limitation on developing CAES is to locate an underground storage vessel that can support the turbo-machinery equipment. *Hydrodynamics* conducted research on technical barriers to the development of solution mined salt beds, aquifers, and depleted gas fields for CAES service. The technical barriers researched for these three CAES storage media are evaluated.

**Keywords**: compressed air energy storage, solution mining, bedded salts, aquifers, depleted gas fields

## INTRODUCTION

The technical barrier to CAES is that air has only been stored successfully in solution mined salt cavities in Huntorf Germany and McIntosh Alabama, and has never been stored in a solution mined salt bed, excavated mine, aquifer, and depleted gas reservoir for use in an energy storage system (proof of concept).

The development of a solution mined cavity in a bedded salt may be constrained by limits on the physical size of the cavity (multiple storage cavities to operate one CAES power plant), removal of insoluble impurities in the salt formation, disposal of the solution mined salt, and potential collapse of the cavity because of plasticity of salt. *Hydrodynamics* evaluated options for resolving these constraints.

CAES in aquifer storage media is problematic because of the constraint of air storage pressure around the hydrostatic pressure of the aquifer, limitations on well productivity, the potential for oxygen depletion, and potential water production with the air. Mitigation of these issues is dependent on the selection of an anticline structure at the proper depth and on highly permeable porous media. The technical feasibility of developing the Dallas Center (Iowa) aquifer structure as a CAES air storage vessel was analyzed using the TOUGH+H2OGas simulator code. The results of this study are used to illustrate the issues with CAES aquifer storage systems.

Air has never been stored in a depleted natural gas field for use as an energy storage system. It is unknown if chemical reactions between air and natural gas will create an explosive environment, or if the stored air would be oxidized to the point that it cannot support combustion of natural gas in the turbine. It is also unknown if it is possible to create an air bubble in a depleted gas field that can store and deliver the required air mass flow rate at a pressure to operate CAES turbo-machinery. The results of *Hydrodynamics* analysis of potential chemical reactions between air and methane reservoirs are presented. The merits of CAES in a depleted natural gas field are also presented.

## CAES IN SOLUTION MINED SALT FORMATIONS

Natural gas and air have been stored successfully in solution-mined salt cavities because of the depth of the salt and the impermeability of the salt. Salt is an attractive medium because it functions as a self-healing material. The process of solution mining causes the salt to re-crystallize along the cavity walls creating an essentially impermeable surface. The crystallized salt membrane, the exceptionally low matrix permeability, and the plastic nature of salt enable it to seal secondary fractures in the rock to create a nearly ideal gas storage vessel. In salt caverns, natural gas and air storage pressure ranges can exceed hydrostatic pressure for extended periods without impairing the integrity of the storage cavity.

The two main types of salt formations available to host caverns are diapir or placement structure domes, common in the Gulf Coast and East Texas Basins, and bedded salt (Figure 1). The characteristics of dome salt and bedded salt are quite different. In the case of dome salts, evaporation of ancient seas left salt deposits that were buried by sediment. Because the salt deposits are less dense than overlying rock the buoyant mass of salt mushrooms upward into the overlying rocks through faults or fractures. The intruding salt dome is called a salt diapir. Typical dome salts are relatively pure and homogeneous. The lateral extent of salt domes is limited, and therefore the dome margins limit the area useful for cavern development. Concentration of the impurities in salt produces a cap rock at the top and, in some locations, sides of the domes. A typical cap rock is an anhydrite that has low permeability and protects the dome from dissolution.

Bedded salt are much less pure than dome salt and can be inter-bedded with limestone, dolomite, anhydrite, polyhalite, and fine-grained siliciclastic mudstone, siltstone, and sandstone. The distribution of these low-solubility impurities is one of the limitations of engineering solution-mined caverns. Salt beds are typically continuous over large areas. Salt beds are also typically thin, pinch out, or change facies laterally into other rock types. In salt beds it is also common that the concentration of impurities does not form a cap rock but rather, forms a heterogeneous and mechanically weak insoluble residue.

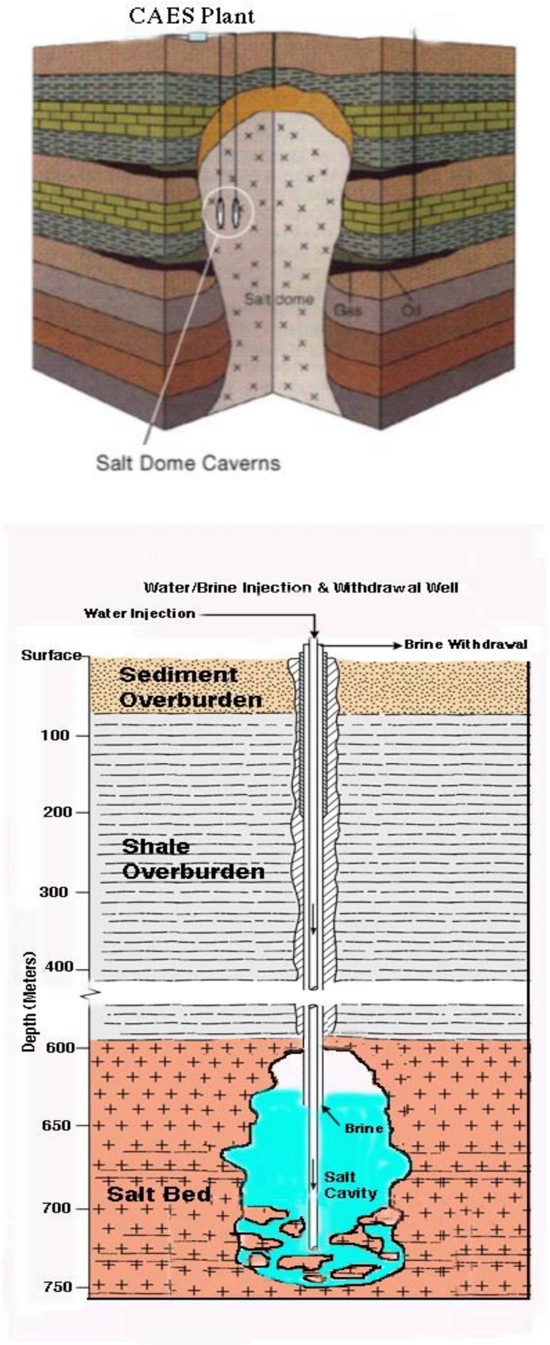


Fig.1 *Sketch of Salt Dome and Bedded Salt CAES Storage Cavities.*

The process of solution mining of salt typically forms elongated, irregular shaped cavities within the salt bed or salt diapir structure (Fig. 1). The solution mining of salt employs the injection of water through a well into the salt bed or dome structure. The water solution with dissolved salt (brine) is then extracted through the annulus of the water injection well for disposal at the surface (Fig. 1).

The viability of development of salt formations for an energy storage project has been demonstrated by over 60 years of successful natural gas, oil, and other hydrocarbon storage projects. The McIntosh Alabama CAES project has successfully operated for many years utilizing a solution-mined salt dome cavity. Our evaluation of bedded salts in west Texas, New York, and Northern Ireland have identified potential issues concerning development of solution mined bedded salt cavities for CAES service. Factors that impact the development and use of solution-mined bedded salt cavities are:

- Limits on the physical size of the cavity,
- Removal of non-soluble impurities in the salt formation,
- Disposal of the solution mined salt, and
- Potential collapse of the salt formation.

Of these factors, the presence of multiple thin lenses of insoluble impurities in the salt formation and the thickness of the salt beds relatively to the strength of the rock formation are the most problematic. These two major issues are illustrated in Fig. 2 on a geological log of the United States Department of Energy core hole in west Texas, borehole DOE/F Grabbe No. 1. Four salt beds (A through D) were identified as potential CAES salt cavity intervals. Our CAES analysis of each of these salt beds is provided in Table 1.

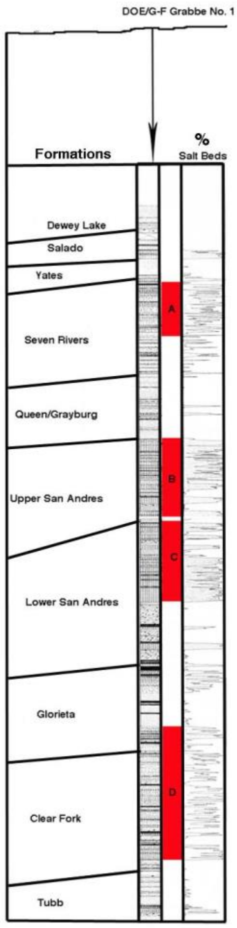
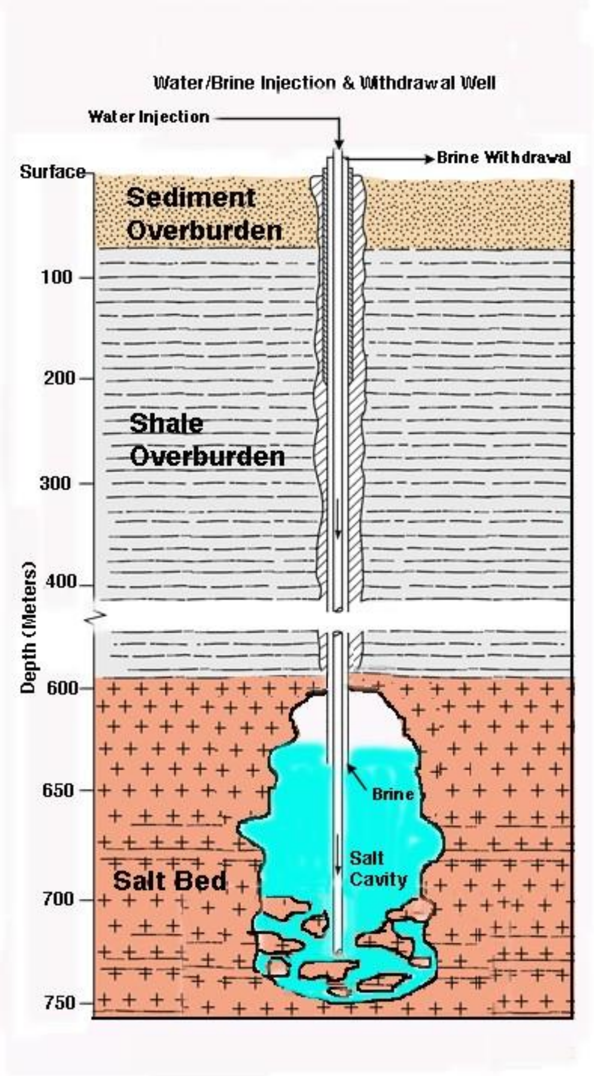


Fig. 2. *Geological Log of DOE/F Grabbe No. 1 Showing Key Salt Beds.*

Table 1. DOE Grabbe Federal #1: Potential CAES Salt Bed Volume Evaluation.

| Salt Bed | Depth Interval | Net Salt Thickness | Potential Cavity Volume | No. of CAES Cavities |
|---|---|---|---|---|



## CAES IN AN AQUIFER STORAGE MEDIA

CAES in an aquifer storage media is problematic. Typically geological data for aquifer structures is very limited resulting in a costly exploration, field-testing, and analysis development programs for a site. It is also problematic in the need to constrain the air storage pressure around the hydrostatic pressure of the aquifer, limitations on well productivity, the potential for oxygen depletion, and the potential of water production with the air. Mitigation of these issues is dependent on the selection of an anticline structure at the proper depth and choice of a highly permeable porous media (Fig. 3). The presence of a cap rock above the air storage zone is also a key factor. Verification of the integrity of the cap rock in an aquifer storage structure for purposes of project development can only be confirmed by the injection of a test volume of air, often at considerable cost. In addition, exploratory drilling is necessary to confirm the geometry of the confining geological structure. Thus, the siting criteria are essential to the success of a CAES aquifer storage system.

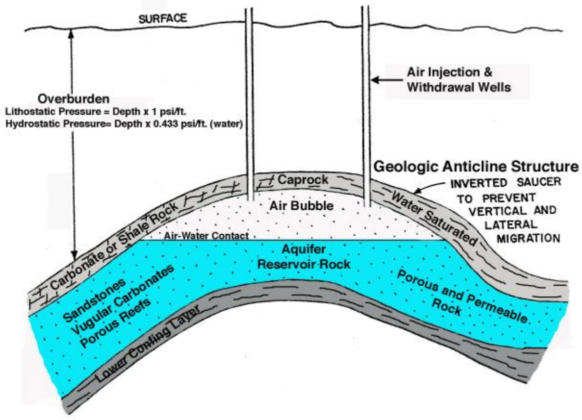


Fig. 3. *Sketch of Aquifer Air Storage Structure*

CAES in an aquifer storage system works most efficiently if the pressure differences between the injection and the production cycles do not vary widely (Fig. 4). This principle leads to maintaining a large volume of air in the reservoir and maintaining a more or less constant pressure to keep operating costs lower. The air that remains in the reservoir is the so-called *cushion air*. CAES reservoir models of various potential aquifer structures in the United States show that the minimum air bubble necessary to support one Dresser-Rand 135 MW power unit is 8 billion cubic feet (Bcf) of air.

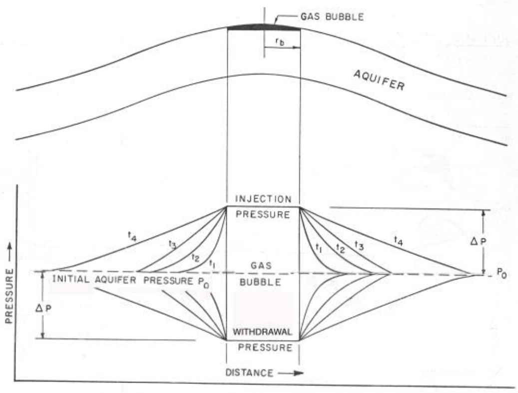


Fig. 4. *CAES Air Storage Pressure Cycle Relative to Hydrostatic Aquifer Pressure.*

Deliverability (*i.e.*, the rate at which air can be withdrawn from storage) is generally considered the key design criterion for an air storage reservoir and is a critical factor in selecting a CAES storage structure. The air mass flow rate needed to support one Dresser Rand 135 MW power unit is 400 pounds per second (#/sec). This equates to 467 million standard cubic feet per day (MMscfd) air flow rate from the air bubble in the aquifer. This is considered a significant airflow rate from and individual air/gas field, and was the limiting CAES design factor for the Dallas Center structure. The airflow rate can only be achieved in a porous media aquifer storage system using multiple air injection and withdrawal wells, unlike a single large diameter well in a solution mined salt cavity system. The number of wells depends on the permeability of the selected porous media air storage formation.

The Dallas Center CAES candidate geological structure in Iowa is a prime example of why aquifer CAES storage systems are problematic; we started with essentially no direct geological data to say without reservation that the structure will work as a CAES storage vessel. *Hydrodynamics* stated that the collection of necessary geological data would take considerable time and money. We also stated that at the end of any exploration program we may only be 60% to 85% confident the site will meet economic design goals, and that a costly air injection program will be required to raise our confidence level to 90%.

Air storage in an aquifer is extremely complex requiring multiple and simultaneous calculations of fluid phase behavior of air and aquifer fluids in the host rock in both a horizontal and vertical direction over a several mile area. Simple hand calculations or rules of thumb petroleum engineering tools are not applicable to this research program. Therefore, our primary tool to evaluate the technical feasibility of a Dallas Center Mt. Simon structure CAES system was the TOUGH+AIR numerical reservoir simulation computer model code.

The TOUGH+AIR code was used for the numerical simulation of this problem, as previously noted. The development of our Dallas Center CAES system model using the TOUGH+ code first required the input of our geological framework model of the Dallas Center Mt. Simon air storage structure. The geometry of the Dallas Center Mt. Simon dome structure shown in Fig. 5 was digitized into the model grid system. The Mt. Simon aquifer was bounded by the relatively impermeable Eau Claire caprock and the pre-Cambrian clastic basement rock. The Mt. Simon aquifer was not bounded in the horizontal direction. The Mt. Simon sandstone is divided into 57 individual geological lenses with the porosity and permeability of each lens determined from Sandia Laboratory rock core test program. The aquifer was assumed to be 100 percent water saturated.

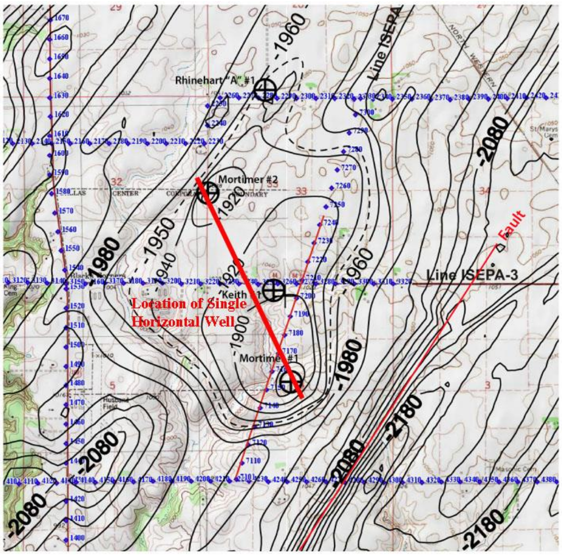


Fig. 5. *Location of Single Horizontal Well in Dallas Center Mt. Simon CAES Storage Vessel*.

A sketch of the Dallas Center Mt. Simon CAES vessel is provided in Fig. 6.

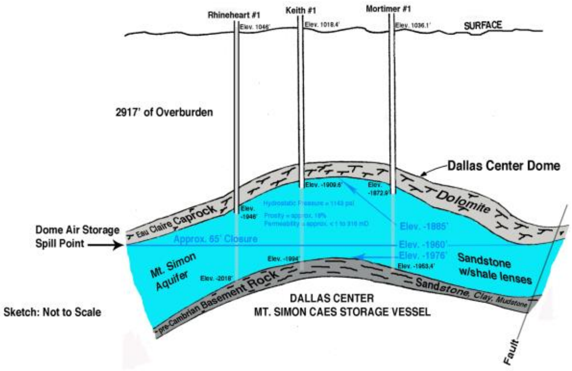


Fig. 6. *Sketch of Dallas Center Mt. Simon CAES Storage Vessel.*

The modeling process first required the development of a Geological Framework Model of the Dallas Center Mt. Simon geological structure to define the configuration and boundaries of the aquifer system. The framework model also defined the vertical and horizontal distributions of the geological units (lenses of different rock types) through the Mt. Simon and defined the porosity and permeability of these lenses over the total structure. The second element of the modeling was to simulate the creation of an air storage bubble in the Mt. Simon structure and then try to simulate delivery of air from the storage system at the require air mass flow rate at a pressure necessary to operate a range of CAES turbo-machinery.

Two different well designs were studied. The first involved horizontal wells, and the second a set of vertical wells. The horizontal wells and the vertical wells were aligned with the axis passing by the crests of the two domes (see Fig. 7).

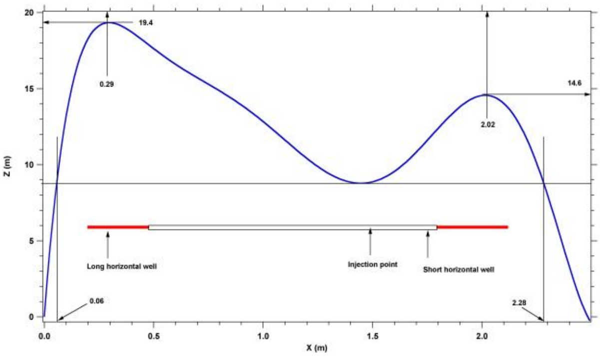


Fig. 7. *Cross section of the Dallas aquifer on the x-z plane along the curved line connecting the crests of the two domes.*

The configurations we investigated were arrived at after the evaluation of several alternative scenarios, and represent the optimal placement (and, in the case of vertical wells, the minimum number of wells) to supply the necessary minimum air flow rate without resulting in excessive pressures during injection (= 0.65 x Lithostatic pressure = 14.4 MPa at the top of the dome = 2090 psia), or cavitation (i.e., excessive pressure drop caused by inability of the formation to supply the prescribed rate) during production.

Two cases of horizontal wells were investigated. The first (long) horizontal well was 1900 m long, and its location and orientation are provided in Fig. 7, which describes the bi-dome structure along the curved line connecting the tops (centers) of the two domes. The second case involved a shorter horizontal well (1200 m), and was considered for reasons explained below.

The vertical well system comprised of 15 wells at 150 m intervals from each other on a slightly curving line that passed by the dome crests and followed the geometry of the part of the aquifer considered for CAES. The first well was located 150 m from the left boundary of the dome shown in Fig. 7. The wells were completed within the structure considered for CAES (see Fig. 7); their perforated intervals extended from 3 m above the base of the structure to the top of the structure.

The results of our Dallas Center CAES system performance analysis showed that:

1. A horizontal well system is unable to support a 135 MW power plant because of pressure drops below the minimum operating pressure (Fig. 8). The analysis shows that the required air storage bubble cannot be successfully filled with air because of the multiple low permeability lenses in the Dallas Center Mt. Simon aquifer.
2. Excessive pressure loses in the Mt. Simon aquifer were also observed in our simulation of CAES air bubble development using 15 vertical air injection wells.

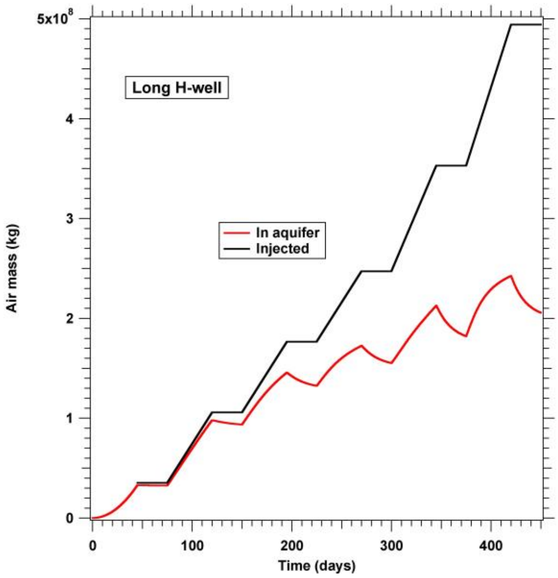


Fig. 8. *Evolution of air mass in the aquifer during fill-up (see Fig. 7) using a long horizontal well.*

As a result of this analysis, the Iowa Stored Energy Park Agency abandoned the Dallas Center CAES project.

## CAES IN A DEPLETED NATURAL GAS RESERVOIR

Natural gas has been contained in deep geological structures for millions of years. We have over 60 years of experience using depleted gas storage fields for seasonal natural gas storage service. Because of this experience, CAES in depleted natural gas fields is considered technically feasible. The merits of using a depleted gas field for CAES are that we:

1. Know the structure can contain air,
2. Typically know the pressure history of the reservoir, and
3. Typically know the gas or airflow potential of individual wells.

*Hydrodynamics* has evaluated the CAES potential of depleted natural gas structures in Nebraska, Montana, Texas, and California. The technical feasiblity of developing these structures for CAES focused on the storage capacity and air bubble development schedule, air mass flow rate potential of required air injection/withdrawal wells, and on potential detrimental chemical reactions from mixing air and residual natural gas in the reservoir. Key results of our research are discussed below.

Natural gas is found in both water drive aquifer structures and in stratigraphic gas trap structures. A water-drive gas field behaves like any aquifer air-water storage system but with three phases of flow: air, natural gas, and water. Stratigraphic gas traps are described as “volumetric” type gas pools. CAES works in both types of depleted gas reservoir because of the space in the porous reservoir left by the natural gas produced from the field. The development of a depleted gas field will require the injection of several BCF of compressed air into the center of the reservoir to create an air bubble to replace the natural gas produced from the field (Fig. 9) and, in an aquifer, to displace water.

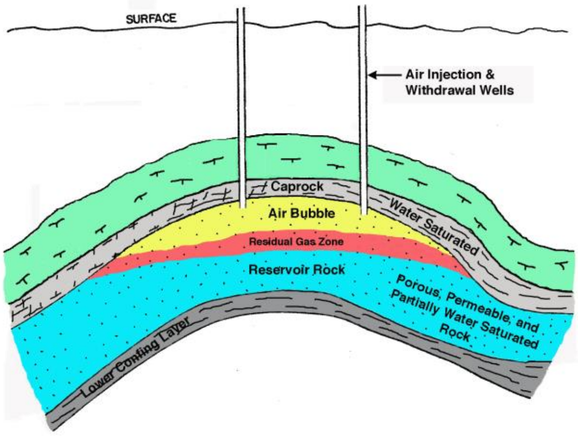


Fig. 9. *Sketch of Depleted Gas Field CAES Storage System.*

The compressed air will displace the remaining natural gas toward the perimeter of the gas bubble. The resulting air/gas bubble can be divided in the three sections of 1) working air center, 2) oxidized air cushion, and 3) natural gas perimeter (Fig. 10).

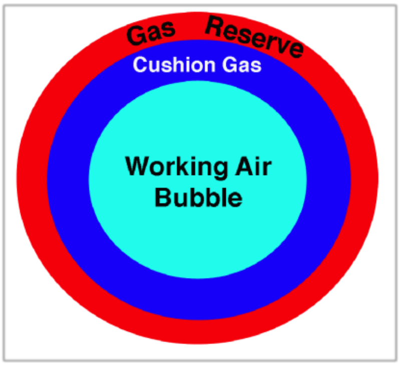


Fig. 10. *Sketch of CAES Air Reservoir in a Depleted Gas Field.*

The two key factors evaluated are: 1) the required rock permeability will support the air mass flow rate at a pressure adequate to operate the CAES turbo-machinery, and 2) determination that any chemical reactions between air and natural gas will not consume oxygen to the point that the withdrawn air cannot support combustion of natural gas in the turbine, and will not form an explosive environment that could impact CAES operations.

### CAES Reservoir Permeability Analysis

The permeability of the target air storage sandstone is critical to the potential air deliverability of the storage system for the required 467 MMscf/day flow at a minimum pressure of 820 psi. *Hydrodynamics* evaluated a sandstone formation in a candidate California depleted gas field to determine the minimum reservoir permeability necessary to support the required air mass flow rate.

For purposes of this analysis we assumed a radial flow model (Fig. 11) that is defined in Equations (1) and (2).

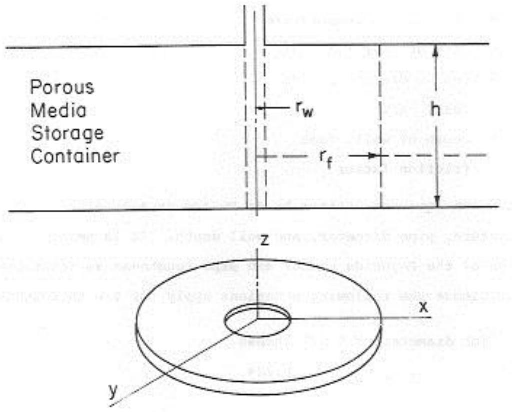


Fig. 11. *Sketch of a Radial Flow Well Model.*

$$(\mathbf{P_f}^2 - \mathbf{P_w}^2) = \frac{(3.418 \times 10^7) \times \mathbf{T} \times \mathbf{z} \times \mathbf{u} \times \mathbf{Q}}{\mathbf{K} \times \mathbf{h}} \times (\ln \mathbf{r_f}/\mathbf{r_w}) \quad (1)$$

Where reservoir properties for the selected sand are:

Q = production rate (MMcf/day)1.134 MMcf/day at $P_f$
$P_f$ = Average reservoir pressure (psia) 1430 psi
$P_w$ = Flowing bottom hole pressure (psia) 1360 psi
T= 460˚ + ˚F = Rankine 570˚ R
z = compressibility factor of 0.80
u = gas viscosity, cp 0.018 cp
K = permeability, mD
h = reservoir thickness, ft. 10 ft.
$\mathbf{r_f}$ = radius of influence, ft. 10 ft.
$\mathbf{r_w}$ = well radius, ft 0.25 ft.

$$K = \frac{(3.418 \times 10^7) \times T \times z \times u \times Q}{(P_f^2 - P_w^2) \times h} \times (\ln r_f/r_w) \quad (2)$$

The calculated minimum permeability is:

$$K = \frac{(3.418 \times 10^7) \times 570^\circ \text{ R} \times .8 \times .018 \times 1.134 \text{ MMcf/D} \times (\ln 10/.25)}{(1430^2 - 1363^2) \times 30 \text{ ft.}}$$

$$K = \frac{318{,}143{,}064.96}{(2{,}044{,}900 - 1{,}857{,}769) \times 10} \times (3.6)$$

K = 612 mD

For this depleted gas reservoir, a permeability of 612 mD is adequate for CAES operation, and will require up to 23 wells to deliver the required 467 MMscf/day.

### Potential Chemical Reaction Analysis

A CAES plant is designed to last 25-30 years. Oxygen consumption rates that are so slow that they do not adversely affect operation over 25-30 years are of little interest. Conversely, reactions that are so rapid that oxygen loss in the compressed air during daily cycles renders plant operation uneconomic would justify rejection of a reservoir unless pretreatment of the reservoir were feasible. Between these extremes lies a range of reservoir oxygen consumption rates that must be quantified to permit CAES plant design optimization.

The subsurface environment in most porous sedimentary rocks is chemically reducing, i.e. it will tend to reduce oxygen to a lower concentration. Free oxygen cannot exist without reaction with the substances present that cause the reducing conditions. These conditions were initially induced by anaerobic authigenic decay of organic matter, which in turn caused the reduction of sulfate and nitrogen and formation of thiol and amino functional groups on the organic matter, and reduction of ferric iron to the ferrous state.

The injection of air into this chemically reducing environment will result in chemical reactions between:

- air and natural gas
- air and connate water
- air and reservoir host rock

The minimum $O_2$(g) concentration necessary for CAES plant operation depends on the plant design and whether conventional or novel technology is used. With steam injection, for example, the low-pressure combustor requires a minimum of 12% $O_2$(g). The recovered compressed air from the reservoir must therefore contain at least 15% $O_2$(g).

Additional issues of concern to a successful CAES operation are inadvertent ignition of natural gas entrained in compressed air in the well bore during compressed air recovery, the formation of explosive concentrations of organic peroxides, and consumption of oxygen in the compressed air due to pyrite oxidation. Other issues of moderate concern include:

LTO (Low Temperature Oxidation), respectively, of natural gas and liquid hydrocarbons and solid hydrocarbons. The remaining issues of concern generally rank low to very low in most reservoirs. This analysis focuses on oxidation reactions between air and methane and potential of combustion or explosion

### *Oxidation Reactions Between Air and Methane*

The impact of oxygen consumption on the operation of a CAES plant can be established if the rates of oxygen consumption in the reservoir can be predicted. In our analysis, this requires the formulation of an oxygen consumption model for incorporation in a mathematical simulator of the CAES system. Typical CAES operating conditions were simulated to determine under what conditions, if any, oxygen consumption in the reservoir would adversely affect CAES plant operation or power output. The model showed less than 1% methane in the working air bubble.

Hydrocarbons are subject to differing oxidation mechanisms, depending on temperature, and it is therefore convenient to divide discussion of the subject into LTO and high temperature oxidation (HTO) mechanisms, respectively. Although the subdivision is somewhat arbitrary, certain distinct mechanisms dominate in each category, which allows a distinction to be made (see Glassman, 1996, Chapter 3). In general, most LTO processes take place below 300ºC, whereas HTO processes take place at temperatures ranging greater than 300ºC.

The following oxidation scheme for the LTO of methane, the principal component of natural gas, is described by Glassman (1996), and is assumed to proceed through the following steps:

1. <u>Chain Initiation</u>
   $CH_4 + O_2 \longrightarrow \bullet CH_3 + HO_2\bullet$ (3)
2. <u>Chain Propagation</u>
   $\bullet CH_3 + O_2 \longrightarrow CH_2O + \bullet OH$ (4)
   $\bullet OH + CH_4 \longrightarrow H_2O + \bullet CH_3$ (5)
   $\bullet OH + CH_2O \longrightarrow H_2O + HCO\bullet$ (6)
3. <u>Chain Breaking</u>
   $CH_2O + O_2 \longrightarrow HO_2\bullet + HCO\bullet$ (7)
1. <u>Chain Propagating</u>
   $HCO\bullet + O_2 \longrightarrow CO + HO_2\bullet$ (8)
   $HO_2\bullet + CH_4 \longrightarrow H_2O_2 + \bullet CH_3$ (9)
   $HO_2\bullet + CH_2O \longrightarrow H_2O_2 + HCO\bullet$ (8)
2. <u>Chain Termination</u>
   $OH\bullet \longrightarrow$ wall (10)
   $CH_2 \longrightarrow$ wall (11)
   $HO_2\bullet \longrightarrow$ wall (12)

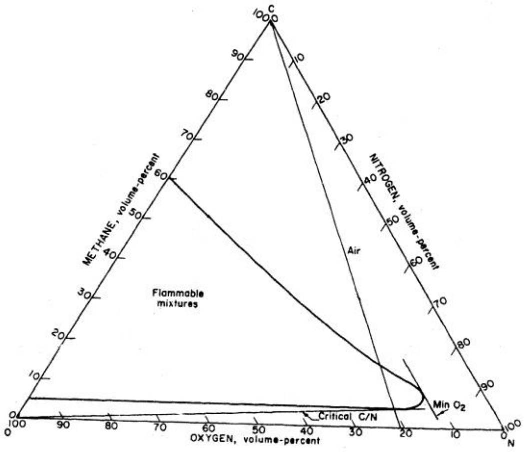
The results of our LTO of methane analysis are as follows:

1. LTO of methane and other low-C alkanes depends critically on the generation of free radicals.
2. LTO rates in the absence of heterogeneous catalysts is so slow that that methane is considered to be essentially inert at 25°C and one atmosphere pressure.
3. The most probable dominant mechanism involving the heterogeneous LTO of methane requires the presence of hydrogen peroxide and a ferric oxide substrate.
4. A reasonable working estimate is to assume complete LTO of methane in 6 months.
5. Calculation based on the above assumed rate, shows that neither oxidation rates nor heat generation will have any significant effect on plant operation at 1 volume percent methane concentration in the compressed air.[

### *Flammability and Potential of Explosion*

A particular concern in utilizing depleted natural gas fields is the potential for accidental ignition of combustible concentrations in the well bore during initial air bubble development. Damage to facilities could be severe, especially if ignition were to lead to the formation of a shock wave traveling up the well bore, which could eventually leads to an explosion.

Fig. 12 shows a triangular composition diagram in which the principal component of a methane–air mixture is displayed at 25ºC and one atmosphere. A large range of mixtures of methane with air can burn when subjected to elevated temperature or exposed to surface catalysts at lower temperatures. Only a limited range of compositions is flammable otherwise. The energy necessary to cause ignition also varies within the range of flammable mixtures, as illustrated in Fig. 13.



Fig, 12. *Triangular composition diagram O-C-N, illustrating the range of flammable mixtures of methane*. (After Zabetakis, 1965).

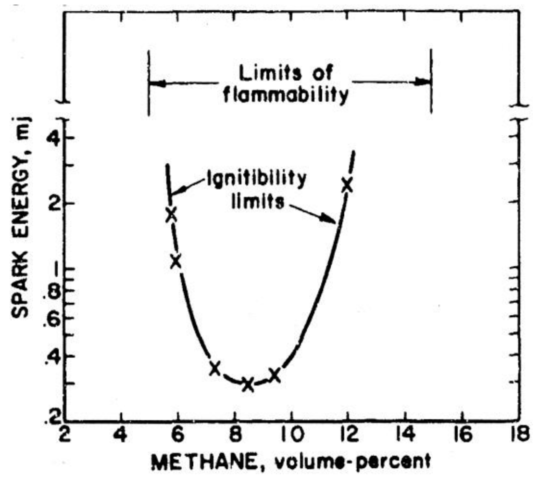


Fig. 13. *Ignitability curve and limits of flammability of methane-air mixtures at one atmosphere pressure and 26ºC*. (From Zabetakis, 1965)

The findings relating to this issue are as follows.

1. The lower and upper flammability limits of methane-air composition representative of the deep geological reservoirs are 3.8 mol% (lower limit) and 54.4 mol% (upper limit) at 25ºC and 85.5 atmospheres.
2. Although any concentration of natural gas above the lower limit and below the upper limit could be ignited and continue to burn, the over-pressure generated near this lower limit remains modest. The overpressure increases, however, until the molar ratio of the methane and oxygen becomes stoichiometric at ≈ 9 mol %, at which point the mixture is explosive.
3. Spontaneous ignition of any flammable mixture of natural gas under ambient conditions in the gas sand is not possible, as pressures on the order of 4500 bar would be required, or a temperature of about 750–800ºC.
4. Ignition of the flammable mixture below the auto ignition temperature requires a spark whose energy input is at a minimum near the stoichiometric composition for complete combustion, but increases as the natural gas mixture becomes progressively more dilute. Therefore, not only are gas compositions near the flammability limit less hazardous if ignited, but also greater energy input is required for ignition.
5. Ignition of combustible mixtures of natural gas within the formation, as opposed to the well bore, is considered to be highly unlikely, as no obvious source of ignition exists, and local ignition is likely to be quenched through heat transfer to the rock matrix, which has a significant heat capacity.
6. The solution to a potential explosive gas mix in a wellbore is to purge the well with nitrogen prior to initial air injection.

## SUMMARY OF RESULTS AND CONCULSIONS

Our analysis indicates that only earth based geological structures can currently store adequate potential energy in the form of a pressurized air mass required by commercial CAES turbo-machinery. Solution-mined salt cavities in dome salts are a proven technology as demonstrated by the Hurtorf and McIntosh CAES facilities. *Hydrodynamics'* research into the development of bedded salts, aquifer structures, and depleted gas fields identified candidate site selection and development issues and defined storage media characteristics necessary for CAES development and operations. Specific results and conclusion are:

### Bedded Salts

1. Limits on the physical size: multiple cavities are necessary to support a 135 MW CAES plant.
2. Multiple lenses of insoluble impurities in the salt formation significantly reduce storage potential of a specific bed.
3. Potential for collapse of the salt formation exists because of the weakness of salt lenses.

### Aquifers

1. CAES in aquifer structures is problematic: the need to constrain the air storage pressure around the hydrostatic pressure of the aquifer, limitations on well productivity, potential for oxygen depletion, and potential water production with the air.
2. An extensive geological exploration program is necessary to characterize the structure with a high potential of failure.
3. Multiple shale lenses within a target CAES formation will prevent development of a homogenous air bubble.

### Depleted Gas Fields (DGFs)

1. DGFs are well suited for development as a CAES storage facility.
2. A reservoir permeability of 600+ mD is adequate to support required air mass flow rates.
3. There are only a limited number of DGFs with adequate matrix permeability to support required air mass flow rates.
4. Oxidation reactions between air and residual methane are: 1) LTO reactions, 2) can be managed through reservoir development, 3) complete LTO of methane can be complete in 6 months, and 4) neither oxidation rates nor heat generation will significanty affect plant operation at 5 volume percent methane concentration in the compressed air.
5. The potential for flammable conditions is limited to the initial fill of a wellbore, and spontaneous combustion in the reservoir is a non-issue.

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