A BRIEF HISTORY OF SALT CAVERN USE

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A brief history of salt cavern use is presented, beginning with the storage of liquid and gas hydrocarbons around five to six decades ago, and continuing to the present. Current main uses of salt caverns worldwide, including storage of hydrocarbons and disposal of wastes, are described. A number of unusual uses, both existing and proposed, are cited. Some problems that have occurred with the use of salt caverns are also noted. Advancements made in salt cavern use are summarized in the conclusion.

1. INTRODUCTION

Salt has been mined over the millennia for consumption and food preservation [1,2]. Underground mining of salt in Austria and Romania may have begun in the New Stone Age [3]. By contrast, the use of underground caverns (or cavities) formed by solution mining of salt has occurred over only about the last five to six decades [4]. The legal issue of "Who Owns the Hole When the Salt is Gone?", relative to storage rights in solution-mined caverns, was addressed as recently as the Sixth Salt Symposium [5].

The objective of this paper is to present an overview of the development of salt cavern use, and the current international status of those uses. A review of previous Salt Symposia Proceedings, now spanning the past 38 years, reveals that the number of papers involving cavern use comprises a generally increasing trend with time. Thus, it is not unexpected that the subject of cavern use represents a major topic at this Symposium in the Year 2000.

2. EARLY DEVELOPMENTS

Storage of both liquids and gases in solution mined salt caverns was reportedly first conceived in Canada in the early 1940's, during World War II [4]. Storage in salt caverns of liquid petroleum gas (LPG), and other "light hydrocarbons" spread rapidly in the early 1950's in North America and several European countries. Storage of crude oil reportedly occurred first in England, also in the early 1950's, during the "Suez Crisis" [6]. Natural gas storage followed storage of liquid hydrocarbons by about a decade in the U.S. and Canada.

Disposal of wastes in salt caverns began initially as a convenient on-site method for discarding of "byproduct" from nearby industrial plants that utilized brine as a feedstock. A number of waste products are disposed of in salt caverns today, however disposal of wastes classified as hazardous generally meets strong local opposition.

The (first) Symposium on Salt was held in 1962 in Cleveland, Ohio [7]. The technology of cavern storage, including the use of Sonar, was described [4, 8]. The 1961 conversion of a depleted brine cavern, Morton Number 16, for storage of natural gas near Marysville, Michigan, was noted [9]. This project has been cited as the first storage of natural gas in a solution-mined salt cavern [10]. However, according to the 1962 Symposium, salt caverns were also in use for storage of natural gas at Hutchinson, Kansas, and for storage of "artificial" gas at Tees, England [11]. As for deep operations, LPG was being stored at depth of 8400 ft (2560 m) [12].

The Second Symposium met in 1965, also in Cleveland [13]. Solution mining of better cavern shapes (by methods begun in 1961) was described [14], as well as construction of a horizontal LPG storage cavern with length over 400 ft (120 m) in thin bedded salt [15].

So, how far have we advanced in the use of salt caverns since "early developments"? Many of the topics listed almost forty years ago remain very familiar. We will return to this question after discussing further developments in cavern use.

3. MAIN USES

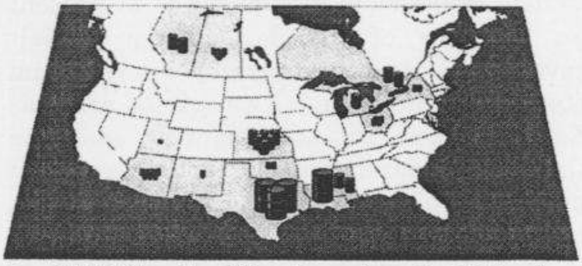
Salt caverns basically constitute very large underground openings that provide secure containment for materials that do not dissolve salt. In general, uses of salt caverns can be classified as either storage or disposal operations. Storage of liquid and gaseous hydrocarbons, and associated products, was successful early on, and remains the main use of salt caverns today. Disposal of wastes and "by-product" constitutes the next most important use of salt caverns. Some examples of these two main types of operations follow.

Salt formations and hydrocarbon deposits, with associated refineries, often occur in the same area, e.g., the Gulf region of the U.S. and Mexico [16]. Many caverns have been solution mined in salt domes here, both to produce brine as a "feedstock" for chemical plants, and to provide for storage of hydrocarbons. Early storage was done in brine "wells" that had been solution-mined without consideration for subsequent storage in the depleted caverns. This practice sometimes resulted in later problems for storage operations in retrofitted brine caverns. Today's brine producers are generally aware of potential storage opportunities, and so use controlled solution mining to produce brine while also forming caverns that are suitable for storage.

A number of salt caverns have been engineered for storage of hydrocarbons and related products, over about the last three decades [17]. The performance of these caverns constitutes a success story for bulk storage of highly volatile materials. Storage of "light hydrocarbons", via the "brine displacement method" [18], represents the first and most widespread use of salt caverns worldwide. Light hydrocarbons include propane, butane, ethane, ethylene, natural gasoline, and other products extracted from refineries and natural gas that are transported and stored as liquids [19].

Figure 1 depicts the distribution of salt cavern storage for light hydrocarbons in the U.S. and Canada. Salt caverns in Texas provided 58% of the total storage, with the Barber's Hill dome, located about 25 miles (40 km) east of Houston at Mont Belvieu, providing 36% alone. The storage facilities concentrated here form a "market hub" for LPG in North America.

"Crude oil", or unrefined petroleum, is also stored in brine-compensated salt caverns. The German Federal Republic implemented its strategic oil reserve in the Etzel salt dome near Wilhelmshaven between 1971 and 1978, creating a total of cavern storage volume of 13 million m³ (82 MMB) [20]. A number of these caverns have since been converted to gas storage. The U.S. began fill of its "Strategic Petroleum Reserve (SPR)" in salt in 1978, and



• = 1 MMB = 1 million barrels = 1.59E5 m³
▮ = 10 MMB
▮ = 100 MMB

Figure 1. Light Hydrocarbons in Salt Caverns in the U.S. and Canada

(Based on GPA 1997 Survey [19])

continued into the early 1990's, to attain a total of slightly less than 94 million m³ (600 MMB) [21]. The "Louisiana Offshore Oil Port (LOOP)" in the U.S. was constructed by a consortium of oil companies in 1981 [22]. LOOP oil storage is provided by 9 caverns in the Clovelly dome with a total volume of about 51 MMB (8.1 million m³) [23]. Other countries with salt caverns providing oil storage are indicated in Table 1.

Table 1
Existing Storage in Salt Caverns

Country	Light Hydro-carbons 1000 m^3	Crude Oil 1000 m^3	Natural Gas 1000 m^3
Canada	6620.4[a]	- - - -	552720[b]
Denmark	- - - -	- - - -	xxxx[c]
France	xxxx	- - - -	xxxx[d]
Germany	xxxx	xxxx	5040.1[e]
Iraq	xxxx[f]	- - - -	- - - -
Mexico	- - - -	1500[g]	- - - -
Morocco	xxxx[c,g]	- - - -	- - - -
Poland	- - - -	- - - -	143000[h]
Russia	465 - 750	- - - -	60 – 180[i]
U.S.	85221.2[a]	102100	3423250[b]

(1000 m^3 = 6289.8 bbl)

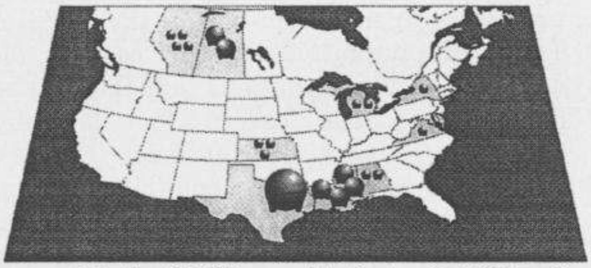
Symbols and Data Sources:

xxxx Storage present, data incomplete
- - - - Lacking data on storage
a Gas Processors Association (1997)
b American Gas Association (1998)
c F. Crotogino, KBB
d B. Brouard, P. Berest, Ecole Polytechnique
e R. Rokahr, University Hannover
f M Dussaud, SOFREGAZ U.S.
g De Laguerie, GEOSTOCK
h K. Urbanczyk, CHEMKOP
i [41]

In recent years natural gas has become a prime source of energy worldwide. Once "flared" as a by-product in oil fields, natural gas was thought to be of short supply in the mid 1970's. It has since been discovered in relative abundance, and is considered to be a "clean burning" fuel. Consequently, most of the recent storage projects in salt caverns have involved natural gas.

Salt caverns engineered for gas storage were constructed in 1963 in Saskatchewan, Canada, at a depth of 3,700 ft (1,128 m). This was followed in the U.S. in 1970 by completion of two gas caverns in the Eminence Dome, Mississippi, at depth of 5,700 to 6,700 ft (1,737 to 2,042 m) [10]. The Eminence caverns were both deep and non brine-compensated, and thus incorporated the potential for large volume loss due to salt creep. In France, gas storage in salt began in 1970 at Tersanne, at depth of approximately 1400 to 1500+ m (4,593 to 4,921 ft) [24]. Gas storage in the salt dome Honigsee, near Kiel, Germany, began in 1971 at depth of 1307 to 1335 m (4,288 to 4,380 ft) [25].

Figure 2 depicts the distribution of natural gas storage capacity in salt caverns in the U.S. and Canada [26]. Table 1 lists data on natural gas storage in salt caverns for a number of countries in North America and Europe. Some of these data are not current. Additional storage facilities in salt caverns are undoubtedly now being planned or constructed because of the increasing use of natural gas worldwide.



• = 1 bcf = 1 billion cubic feet = 2.83E7 m3
● = 10 bcf
● = 100 bcf

Figure 2. Natural Gas in Salt Caverns in the U.S. and Canada

(Based on AGA 1998 Survey [26])

Compressed air energy storage (CAES) was implemented in Germany in 1978 in the

Huntorf salt dome near Hamburg [27]. A CAES plant was also constructed in 1991 in the McIntosh salt dome near Mobile, Alabama, U.S. [28]. CAES plants are used to meet peak power needs, and their future depends on companies now supplying both natural gas and electrical power.

The first wastes placed in salt domes were probably residues from local salt-based industries. Beginning about 1959, alkali wastes from local "soda ash" production were deposited in "worked out" caverns in the Holford brinefield located about 20 mi (32 km) south of Manchester, England [29]. Other salt-industry related wastes, such as "brine muds" from the purification of brine, were also deposited in caverns at Holford. Similar on-site waste disposal was likely practiced at a number of other industrial plants that use locally produced brine, thus forming caverns, in production of soda ash and/or plastics. Another interesting feature of the Holford site is that organic residues generated off site have been deposited there since 1968 in special designated caverns through a partnership between the brinefield operators and a commercial waste disposal firm.

Salt caverns are now being used for disposal of oil field wastes in the U.S. At the time this paper was prepared, the State of Texas had permitted six salt caverns for disposal of non-hazardous oilfield wastes (NOW), and one cavern for naturally occurring radioactive materials (NORM). The states of Louisiana and New Mexico were also in the process of developing regulations for disposal of oil field wastes in salt caverns [30, 31].

The potential for disposal of hazardous chemical wastes in salt caverns has been recognized by companies worldwide. As previously noted, both liquid and gaseous hydrocarbons have been successfully stored in properly constructed salt caverns for decades, and from a technical viewpoint, this would seem to qualify salt caverns for disposal operations of materials with similar properties [32,33]. However, applications to construct hazardous waste disposal facilities in salt in the U.S. have raised far more objections than have applications for storage facilities, or for more traditional forms of waste disposal, such as landfills. Disposal of hazardous wastes in salt domes is banned outright in the State of Louisiana; and, applications for disposal in salt caverns elsewhere in the U.S. have been subjected to lengthy examination [34, 35].

The disposal of high-level nuclear wastes in salt caverns is not discussed here because it involves special considerations beyond those for conventional uses of caverns. It should be noted that research on disposal of nuclear wastes in salt has advanced analyses of conventional salt cavern behavior.

4. UNCONVENTIONAL USES

Some unconventional concepts have been proposed for the use of salt caverns. A number of these are noted here.

Storage of food grains in salt caverns, with pneumatic conveyance systems, has been proposed [36]. Storage of liquid natural gas (LNG) in salt caverns is appealing, because volume requirements are reduced by a factor of about 600 from the gas phase [17]. However, cryogenic temperatures are required, which caused extensive fracturing of salt in an LNG storage test in a German mine [37]. Gas storage volume requirements can also be reduced, by a factor of about 2, by using chilled gas [38]. Examples of unusual material stored in salt caverns include hydrogen and anhydrous ammonia [39], and helium [40, 41].

Unusual cavern configurations have been proposed, and some constructed. Pairs of "Over and Under" caverns in Armenia provide brine-compensated and natural gas driven systems for storing butane [40]. Two-level cavern pairs, utilizing brine and natural gas flowing rapidly between levels, have also been proposed for energy storage in The Netherlands [42].

Waste disposal in a series of vertically separated salt caverns, solution-mined from a common well, has been proposed [43]. The caverns, plugged between levels, would not transfer pressures vertically. The "string of pearls" concept was proposed for disposal of hazardous waste in the Vinton salt dome in south Louisiana in the 1980's. However, disposal of all hazardous waste in salt domes in Louisiana was shortly banned.

To close this subsection we note the unusual use of salt formations in the U.S. for tests of nuclear devices [44]. Two 5-kiloton devices were detonated in salt as events within the "Plowshare" and "Project Dribble" programs, respectively. The events "Gnome" of Plowshare took place in bedded salt near Carlsbad, New Mexico, in 1961, and "Salmon" of Project Dribble occurred in the Tatum dome near Hattiesburg, Mississippi, in 1964. Three additional tests involving explosions of natural gas were performed in the cavity formed in the Tatum salt stock by Salmon. To date no leakage of radioactivity has been reported over the Tatum dome, which can be cited as an example of the exceptional containment properties of salt caverns, given adequate confinement and salt cover.

5. SOME PROBLEMS

Some problems have inevitably occurred with the use of salt caverns over the past decades. These range in character from undesirable cavern behavior to disastrous explosions on the ground surface.

Large volume losses due to salt creep have occurred in natural gas storage caverns. Examples include the earlier cited Eminence dome, U.S., with loss of 40% [45, 46]; and at Tersanne, France, with loss of 30% [24, 47]. Such losses represent costly reductions in storage capacity. Following these early problems, appropriate adjustments were made in cavern depths and minimum operating pressures, so that gas storage continues at both sites today.

Salt caverns storing liquid hydrocarbons have experienced "salt falls" that damaged hanging (casing) strings; and also, gas emissions from the surrounding salt mass that contaminated or caused problems in handling stored products [48-50]. Leakage of an oil storage cavern resulted in efforts to repair it from the inside, with a remotely operated submersible vessel [22, 23].

Equipment failure caused a fatality in 1978 during repair of a casing into a SPR oil storage cavern in Louisiana, U.S. The State of Louisiana subsequently issued Order 29-M, perhaps the first regulations in the U.S. that applied to storage in solution mined salt caverns. In 1980, a leak occurred through corroded casing of a LPG storage cavern in Barbers' Hill dome, Texas. The gas likely moved through porous soil and caused an explosion in a residence in nearby Mont Belvieu [51]. Storage operations at Barber's Hill were subsequently regulated by a specific State Order [52].

A disastrous explosion occurred April 7, 1992, following an outflow of LPG onto the surface from the well of a storage cavern in the Brenham salt dome, located about 70 miles (113 km) northwest of Houston, Texas. Three fatalities resulted from the explosion, which was recorded as a 4+ event on a Richter Scale in Houston. According to early news releases, "A salt dome had blown up". However, the LPG storage cavern later "passed" a mechanical integrity test (MIT). State authorities did not permit further storage of LPG at the site, but not because the cavern had failed. The State of Texas now has comprehensive safety regulations for both light hydrocarbons and natural gas storage in salt caverns [52]. The very unfortunate Brenham disaster, like the previously noted tests of explosive devices in salt, further demonstrated the exceptional containment characteristics of salt caverns.

6. CAVERN EVOLUTION

Most salt caverns result from commercial production of brine. Thus some older "brine wells" display shapes considered marginal or unsuitable for storage or disposal uses. Still, old caverns with unusual shapes and spans comprise serendipitous field tests that demonstrate the in-situ strength of salt formations. For example, a brine cavern in the Bryan Mound dome in the U.S. has a span of about 335 m (1100 ft). Such standing examples encourage construction of larger storage caverns.

Natural gas caverns, with deep cycling of pressure, place more demands on the host salt formation than liquid caverns. Salt caverns designed for natural gas storage started small, and have gradually increased in size. Maximum permitted volumes of gas caverns in Germany started at 350,000 m^3 (2.201 MM bbls), were increased to 500,000 m^3 (3.145 MM bbls), and for the past ten years have been 700,000 m^3 (4.403 MM bbls) [53]. Cavern volumes are not regulated so specifically in the U.S. A natural gas cavern with approximate volume of 15.6 MM bbls (2,480,000 m3) and span of 350 ft (107 m) is now under construction in the Napoleonville dome in south Louisiana [54].

Subsidence over caverns was not thought to be significant during the early phase of cavern use. Operators are now aware that subsidence will occur over caverns, and so take measures to mitigate its effects.

Characteristics of host salt formations dominate cavern configuration design. Thus short, stout caverns are generally sited in bedded salts, whereas tall, slender caverns are often located in salt domes or anticlines. A number of liquid caverns in Gulf Coast domes have heights of about 2000 ft (610 m) and spans of 200 ft (61 m), which provides for considerable storage in a small area.

Horizontal caverns obviously "fit" bedded salt formations better than vertical ones, and bedded salt may be available where domes are not. Thus trials are underway of storage caverns formed by controlled solution-mining from horizontally drilled wells, rather than by uncontrolled hydraulic fracturing [55]. Methods for monitoring horizontal cavern shapes and thickness of salt cover are needed to satisfy regulations, and will probably be available soon.

Research on plugging and abandonment (P&A) of old salt caverns is currently underway via support by the Solution Mining Research Institute (SMRI) and U.S. Department of Energy (DOE). The P&A issue appears likely to be site specific, and perhaps long-term in character.

7. SUMMARY AND CONCLUSION

Now we return to the question, "How far have we advanced in the use of salt caverns?" Main applications remain storage of high-energy materials and wastes; still, the design and construction technology for salt caverns has advanced considerably. Validated computer codes are available for predicting mined shapes and creep behavior of caverns, and methods for mapping cavern shapes through multiple casings are in use. Controlled solution mining and monitoring of horizontal caverns appears close at-hand.

At this point in time the technology for salt cavern use can be described as "middle aged". Considerable experience exists for salt caverns, which helps in applying the technology to new sites worldwide.

In conclusion, we ask the related questions: Is that all there is? Or, can we find other uses for salt caverns?

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