TEXAS SALT DOMES: Natural Resources, Storage Caverns, and Extraction Technology

Steven J. Seni, William F. Mullican III, and H. Scott Hamlin

Contract Report for Texas Department of Water Resources under Interagency Contract No. IAC (84-85)-1019

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INTRODUCTION

This report reviews natural resources associated with salt domes in Texas. Salt domes provide a broad spectrum of the nation's industrial needs including fuel, minerals, chemical feedstock, and efficient storage space. This report focuses on the development, technology, uses, and problems associated with solution-mined caverns in salt domes. One proposed new use for salt domes is the permanent isolation of toxic chemical waste in solution-mined caverns. As the Texas Department of Water Resources (TDWR) is the State authority responsible for issuing permits for waste disposal in Texas, TDWR funded this report to judge better the technical merits of toxic waste disposal in domes and to gain a review of the state of the art of applicable technology.

Salt domes are among the most interesting and intensively studied structural-stratigraphic geologic features. Individual domes may be the largest autochthonous structures on earth. Yet many aspects of salt-dome genesis and evolution, geometry, internal structure, and stratigraphy are problematic. Details of both external and internal geometry of salt stocks and their cap rocks are vague, and information is restricted to the shallow parts of the structure. These facts are all the more surprising considering that salt diapirs dominate the fabric of the Gulf Coastal Province, which is one of the most explored and best known geologic regions on earth.

This report includes information on present and past uses of Texas salt domes, their production histories, and extractive technologies (see also Halbouty, 1979; Hawkins and Jirik, 1966; and Jirik and Weaver, 1976). Natural resources associated with salt domes are dominated by petroleum that is trapped in cap rocks and in strata flanking and overlying salt structures. Sulfur occurs in the cap rock of many domes. Some cap rocks also host potentially valuable Mississippi Valley-type sulfide and silver deposits. Salt is produced both by underground mining of rock salt and by solution brining.

The caverns created in salt by solution mining also represent a natural resource. The relative stability, economics, location, and size of these caverns makes them valuable storage vessels for various petroleum products and chemical feedstocks.

TEXAS SALT DOMES

Texas salt structures are clustered in the Gulf Coast, Rio Grande, and East Texas Salt Basins. Shallow piercement salt domes form diapir provinces within the larger salt basins (fig. 1). A regional map shows the distribution of salt domes in the three salt basins (fig. 2). Structure-contour maps (sea-level datum) of individual domes were prepared and plotted on a map with surface topographic contours (appendix 1).

Physically, salt domes are composed of three elements--the salt stock, the cap rock, and the host strata. The central core of the salt dome is a subcylindrical to elongate salt stock. Typically, the cap rock immediately overlies the crest of the salt stock and normally drapes down the uppermost flanks of the stock. An aureole of sediments surrounds the salt stock. Drag zones, gouge zones, and diapiric material transported with the salt stock are included in the aureole.

Salt diapirs are the mature end members of an evolutionary continuum of salt structures. Diapirs begin as low-relief salt pillows that are concordant with surrounding strata. The flanks of the salt pillow steepen with continued growth, and overlying strata are stretched and faulted. Salt becomes diapiric when the relation of salt and surrounding strata becomes discordant. At that point, the salt structure may be intrusive with respect to surrounding strata or it may be extruding at the surface. The phase of active diapirism is typically accompanied by rapid rates of sedimentation. Subsequent to active diapirism, dome evolution enters a slower phase of growth characterized by slow rates of upward movement or by crest attrition owing to salt dissolution in excess of growth.

Dome-growth history is an important aspect in understanding the many problems associated with dome stability (Jackson and Seni, 1983). A complete understanding of dome



Figure 1. Salt basins and diapir provinces in the United States (modified from Smith and others, 1973).

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TEXAS SALT DOMES



(continued)

Figure 2 (cont.).

Code	Dome Name	County
AL	Allen	Brazoria
AR	Arriola	Hardin
BB	Barbers Hill	Chambers
BA	Batson	Hardin
BE	Bethel	Anderson
BC	Big Creek	Fort Bend
BI	Big Hill	Jefferson
BL	Blue Ridge	Fort Bend
BG	Boggy Creek	Anderson/Cherokee
BO	Boling	Wharton/Fort Bend
BR	Brenham	Austin/Washington
BK	Brooks	Smith
8H	Brushy Creek	Anderson
BM	Bryan Mound	Brazoria
BU	Bullard	Smith
8T	Butler	Freestone
CP	Cedar Point	Chambers
CL.	Clam Lake	Jefferson
CC	Clay Creek	Washington
ÇM	Clemens	Brazoria
co	Concord	Anderson
DM	Damon Mound	Brazoria
DN	Danbury	Brazoria
DH	Davis Hill	Liberty
DA	Day	Madison
	Dilworth Hanch	MCMullen
	East lyler	Smith
	Elkhart	Anderson
53 71	Esperson	Harris/Liberty
	Fannett	Jetterson Brazas/Orimon
	Cirlia Caldwall	Brazos/Grimes
	Grand Salina	Smith Van Zandt
GO GU	Granu Sanne	Van Zandt
00 60	Gun Hill	Matagorda
ыл ыл	Holoopuillo	Maad
na ud	Hankamor	WOOD Chamborn /Libortu
ᆈᄰ	Haukinguille	Matagordo
un. Lui		Galvertee
но НО	Hockley	Harrie
нм	Hosking Mound	Brazoria
HIL	Holi	Liborty
	nun	Liberty

ΗВ Humble Harris KΕ Keechi KI Kittrell LR La Rue LP Long Point LL Lost Lake MA Manvei MK Markham MQ Marquez MC McFaddin Beach ML Millican мо Moca MB Moss Bluff MS Mount Sylvan MΥ Mykawa NA Nash ND North Dayton ΟK Oakwood OR Orange oc Orchard PA Palangana ΡĿ Palestine ΡE Pescadito P٩ **Piedras Pintas** ΡJ Pierce Junction PN Port Neches 88 Raccoon Bend RF **Red Fish Reef** SF San Felipe SN San Luis Pass SA Saratoga SO Sour Lake SH South Houston SL South Liberty SP Spindletop ST Steen SR Stratton Ridge sυ Sugarland ТΗ Thompson WE Webster wc West Columbia WH Whitehouse

Anderson Houston/Walker Henderson Fort Bend Chambers Brazoria Matagorda Leon State waters Brazos Webb Chambers/Liberty Smith Harris Brazoria/Fort Bend Liberty Freestone/Leon Orange Fort Bend Duval Anderson Webb Duval Harris Orange Austin State waters Austin State waters Hardin Hardin Harris Liberty Jefferson Smith Brazoria Fort Bend Fort Bend Harris Brazoria Smith

growth requires detailed knowledge of dome geometry, stratigraphy, and structure and stratigraphy of surrounding strata, geohydrology (both past and present), and surficial strata. Such detailed studies have been completed for salt domes in the East Texas Basin (Jackson and Seni, 1984; Seni and Jackson, 1983a, b). Currently, the required data base for understanding growth history of the domes in the Houston Salt Basin is only partly assembled. Public data on the geometry of the salt stock have been collected. Much work remains to understand the geology of cap rocks and surrounding strata.

The influence of dome growth on the topography of the modern surface over the crests of salt structures is one aspect of dome-growth history that is available for domes in both the Houston and the East Texas Salt Basins. The topography of the modern surface over the crests of diapirs is readily influenced by diapir growth or dissolution. Positive topographic relief (in excess of regional trends) over the dome crest is linked to uplift or to active diapir growth. In contrast, subsidence of the topographic surface over the dome crest is linked to attrition or dissolution of the dome crest. Comparison of the topographic relief over domes in the salt basins indicates the relative importance of growth or dissolution processes. For salt domes in the Houston Salt Basin with crests shallower than 4,000 ft, 63 percent of the domes show evidence of positive topographic relief over their crests, whereas only 8 percent of these domes show evidence of subsidence at the depositional surface. In contrast, in the East Texas Salt Basin, 81 percent of the shallow domes (those with crests shallower than 4,000 ft) show evidence of subsidence over the crest, whereas no domes in the East Texas Salt Basin express evidence of uplift. Clearly, strata over the crests of domes in the East Texas Salt Basin have responded differently to processes at the diapir crest than have domes in the Houston Salt Basin. Supradomal topography over domes in the East Texas Basin reflects the dominance of dissolution and crest attrition processes, whereas the dominance of uplift is shown over domes in the Houston Salt Basin.

SOLUTION-MINED CAVERNS

Salt caverns were originally an unrecognized resource formed when salt was removed by dissolution to produce brine principally as a chemical feedstock. Along the Texas coast, a large petrochemical industry evolved because abundant petroleum reserves were associated with Texas coastal salt domes. This close association between salt domes and the petroleum industry in turn promoted both brine and storage industries near the domes. Texas domes are now being considered as chemical waste repositories. The petroleum-refining industry would be the source of much of that chemical waste.

Natural resources from Texas salt domes have been efficiently exploited with a multipleuse philosophy. Permanent disposal of toxic-chemical waste in solution-mined caverns may remove a given region of the dome from resource development forever. Multiple use of domes in the future would then be restricted.

Brining and solution mining are two different operations that form two types of caverns. Brining is used here to describe operations in which the primary economic product is the Na⁺ and Cl⁻ in the brine. Caverns that form around brine wells are incidental to the production of brine. The cavern is just the space from which salt was dissolved during brine production. Solution mining is used here to describe the process of forming an underground cavern specifically for product storage. In this case the brine is typically discarded either into the cap rock or the saline aquifers.

Both brining and solution mining operate on a large scale in Texas. Of 13 domes with a history of brining operations, 7 are active. Similarly, of 18 domes with a history of storage, 16 are active. Two additional domes have proposed storage operations approved by the Texas Railroad Commission (RRC). According to Griswold (1981), approximately 900 cavities have been solutioned in the United States (circa 1981). Statistics from the Gas Processors Association (GPA) reveal that in 1983, 47 percent of the national storage capacity of light hydrocarbons was in Texas salt domes (GPA, 1983).

The primary objectives differ for brine operations and solution mining for storage. Currently, many former brine caverns serve as storage caverns. Simultaneous product storage and brining began in Texas at Pierce Junction salt dome (Minihan and Querio, 1973). The difference between salt dissolutioning to produce brine and creating space for storage may be subtle but variations in operating parameters often produce vastly different salt-cavern geometries. The primary objective in brining is lessening pumping costs and increasing brine production. Solution mining for storage is primarily directed toward a controlled cavern shape yielding maximum cavern stability. The mechanisms by which differences in operating parameters affect cavern shape and stability will be described in sections titled Cavern Geometry, Cavern Failures, and Mechanisms of Cavern Failure.

As with many fledgling industries, initial solution-mining operations were originally seatof-the-pants. Experience was gained from the early operations, and many new techniques were employed to complete successfully and set casing in problem holes, to control and monitor cavern development, and to predict eventual cavern shapes and stabilities. Some predicted conditions later proved wrong, however. Despite industry safeguards, a total of 10 brine and storage caverns have failed in Texas.

Both long-term and short-term cavern stability is a critical issue for the storage industry and especially for the permanent disposal of chemical waste. Despite concerted research effort in this area, even industry leaders admit "no universally accepted technique to predict cavern closure (or stability) has been developed" (Fenix and Scisson, Inc., 1976a).

Public Information

At this point a caveat is warranted. The total number and capacities of solution-mined caverns in Texas is unknown. Most individual companies treat information on cavern capacities as classified data. Much research time and effort were spent at the RRC examining original documents requesting storage permits. Railroad Commission of Texas authority numbers are included in appendix 2 to aid future research efforts. Early regulatory practices of the RRC

were laissez-faire. The original permit specifically allowed any and all improvements including the creation of additional storage caverns and space as desired. Other caverns that received permit approval were never completed. Some caverns have been abandoned as a result of technological or economic problems. Thus although a comprehensive list of caverns approved by the RRC was obtained, its exact equivalence with currently active caverns and their present use is not assured. Capacities of storage for Texas salt domes are from the Gas Processors Association (1983), which lists present storage capacities for light hydrocarbons. Storage of natural gas and crude oil was not listed by the Gas Processors Association. Much additional storage capacity primarily resulting from brining is undocumented.

The RRC created the Underground Injection Control Section and strengthened application procedures and reporting requirements for constructing underground hydrocarbon storage facilities after a storage cavern failed at Barbers Hill salt dome. Beginning April 1, 1982, all storage wells must be tested for mechanical integrity at least once every 5 years. Rule 74 is the document that details State requirements for underground hydrocarbon storage. It is reproduced in appendix 3.

CAVERN CONSTRUCTION

A salt cavern is solution mined by drilling a hole to expose salt, circulating fresh or lowsalinity water to dissolve salt, and then displacing the resulting brine. With time, the hole enlarges and becomes the cavern. Constructing a solution-mined cavern in salt requires thick salt, a supply of fresh or low-salinity water, and a means of disposing or using the brine (Fenix and Scisson, 1976a). With some exceptions, solution-mined wells are drilled and cemented with what is generally the same technology as that is used in completing oil-, water-, and brinedisposal wells. The unique set of conditions generated during cavern dissolution requires some specialized procedures. Hole straightness is critical because this affects cavern geometry and location. Massive drill collars are used to reduce the "walk-of-the-bit," or the tendency of the

bit to trace a helicoidal path during drilling. Drilling in salt also requires special salt-saturated drilling muds for preventing hole enlargement by unwanted salt dissolution.

The casing program is the single most important aspect for successfully drilling and completing a well for solution mining. Industry experts agree that most cavern failures and all reported instances of catastrophic product loss resulted from some form of casing failure (Fenix and Scisson, 1976a; Van Fossan, 1979).

Casing Program

Casing programs for solution-mined wells are designed to (1) prevent contamination of surrounding formations by drilling fluids, (2) prevent sloughing of surrounding formations into the drillhole, (3) anchor the casing, tubing, and braden-head assembly firmly into the salt, and (4) prevent loss of storage products. Casing programs have become more complex with time. A typical casing program is shown in figure 3. Early casing programs in brine wells used two or three casing strings and one production tubing. Modern casing programs use up to seven casing strings and up to three production tubing strings.

<u>Conductor pipe</u> is the first and largest diameter (30 to 42 inch) casing. Conductor pipe is commonly used in the Gulf Coast area where it is simply driven 50 to 300 ft into the ground until rejection. After drilling through fresh-water aquifers in the upper section, <u>surface casing</u> is set and cement is circulated to the surface up the annulus between the surface casing on one side and exposed formations and conductor casing on the other. Typically the surface casing is set at the top or slightly into the cap rock. <u>Intermediate casing</u> is set through the cap rock and from 100 to 500 ft into the top of the salt. Intermediate casing is used to isolate lostcirculation zones that commonly occur in the cap rock. Two intermediate casing strings may be cemented through the cap rock where lost-circulation zones cause severe problems. The intermediate casing is set at a depth in salt sufficient to ensure a good cement-formation bond. Salt-saturated muds are used when drilling into salt. Similarly, intermediate casing is cemented





with specialized salt-saturated and nonshrinking cements. Clearly, a secure cement-formation bond is critical for cavern integrity. Cement is circulated to the surface.

Inner or Product casing is set if the depth of the top of the cavern is significantly deeper than the bottom of the intermediate casing. Again, salt-saturated, nonshrinking cements are circulated at least to the intermediate casing and preferably to the surface.

Salt-Dissolution Process

Two processes--diffusion and circulation--cause salt to dissolve. Diffusion is the ionic movement of Na+ and Cl⁻ ions away from the salt face toward regions of lower ionic pressure in the water. This process is very slow and is not considered the primary mechanism of cavern formation (Bays, 1963). In contrast, circulation implies mass movement of unsaturated fluid to the salt face. The saturation can then be increased as circulation brings additional unsaturated fluid to the salt face. Low-pressure jetting techniques (Van Fossan and Prosser, 1949) are used to create a predictable circulation pattern.

Temperature, gravity, and pressure all influence the circulation process. Thermal convection of the brine within the cavern is due to temperature differences between cold, dense injection water and hotter, stabilized cavity water. Thermal convection is actually a gravity phenomenon of short duration. Temperature and circulation equilibria are achieved within 24 to 72 hours in a stable cavern (Bays, 1963). Gravity is the most important factor controlling fluid movement within a cavern. Injected fresh waters are lighter than brines that are saturated. Thus, injected waters will rise through the brines. Fluids at the base of the cavern are nearly saturated, and fluids at the top of a cavity are rarely more than 10 to 15 percent saturated and may be essentially fresh. Pressure gradients imposed by brine-lift pumps also cause circulation within a cavern. However, as cavern size increases, the circulation effects of pressure differentials become insignificant (Bays, 1963).

Blanket Material and Function

The blanket is inert material at the top of the cavern. The main function of the blanket is preventing unwanted salt dissolution at the top of the cavern around the casing seat. The blanket also prevents corrosion of the product casing. Many materials have been used as blankets including air, diesel oil, crude oil, butane, propane, and natural gas. The blanket must be lighter than water and must not dissolve salt. The blanket material is injected in the annulus between the last or innermost casing string and the outermost wash or blanket tubing. Thus brine is prevented from contacting the casing seat.

Raising or lowering the blanket tubing controls the position of the blanket. The location of the blanket can locally produce a desired cavern shape by dictating where dissolution is allowed to take place. This technique is typically used at the beginning and end of cavern construction, first to wash the sump and finally to dome the cavern roof. A sump is produced at the bottom of the borehole by using a long blanket tubing to depress leaching to the base of the hole. Once the cavern has been leached, blanket control can shape the cavern roof into a dome or arch for added stability. By periodically withdrawing the blanket tubing and raising the level of the blanket during a wash cycle, a flat roof is progressively shaped into a domed or arched roof.

Sump

A sump or local depression is mined at the bottom of solution caverns to collect the relatively insoluble constituents of salt domes that remain after the salt is dissolved and removed (fig. 4). A typical Gulf Coast salt dome contains from 1 to 10 percent anhydrite, which is the chief insoluble mineral. Country rock, sandstone, and shale are insoluble constituents that may be encountered in the salt stock. These insoluble materials generally become more abundant as the periphery of the salt stock is approached. The volume of the





sump is dictated by the volume of the cavern and by the insoluble percentage. A core of the salt mass is normally used to determine percentage of insoluble constituents.

CAVERN GEOMETRY

The two basic techniques to control the shape of the caverns are direct circulation and reverse circulation. The techniques are differentiated by the location of the fresh-water injection and brine-return tubing within the cavern. Additionally the thickness and location of the blanket controls cavern shape during the initial and final stages of cavern mining. Final cavern shape is also influenced by variables that cannot be controlled. Such variables include salt-stock inhomogeneities, percentage and distribution of insoluble constituents, salt solubility, and space limitations with respect to the edge of the salt stock, property lines, or adjacent caverns.

Caverns that were solution mined for storage are typically leached with direct circulation, whereas brining operations typically use reverse circulation. The leaching technique for a single cavern may vary with time to adjust to changing uses or to modify original cavern shapes. The leaching technique is an important factor in cavern stability because each technique produces a "typical" shape. Clearly cavern stability is, in part, a function of cavern shape (Fossum, 1976).

Direct Circulation

A cavern is leached by <u>direct circulation</u> when fresh or low-salinity water is injected down the wash tubing and exits near the base of the cavern (fig. 4). Brine is returned up the annulus between the wash tubing and blanket casing located near the top of the cavern. The freshest water enters the system near the base of the cavern; thus, most of the dissolution is concentrated there. A pressure differential between the injection and brine return helps drive the progressively more saline water upward toward the brine return point. Characteristically

with direct circulation, the discharged brine is less saturated with Na⁺ and Cl⁻ than is the brine discharged during reverse circulation.

A cavern formed by direct circulation is typically tear-drop shaped because fresh water is injected at the base of the cavern and the brine is returned at the top. Cavern geometries after phased expansion using direct circulation are shown in figure 5.

Reverse Circulation

A cavern is leached by <u>reverse circulation</u> when fresh water is injected down the annulus between the blanket casing and the wash tubing. The fresh-water injection point is at the top of the cavern. The brine returns up the wash tubing for which the opening is located near the base of the cavern (fig. 6). The typical geometry of a cavern leached by reverse circulation is "flower pot" with a characteristically broad and flat roof. Density differences between fresh water at the top and brine at the base allow brine to sink toward the base of the cavern. The lighter fresh injection water is forced to circulate near the top of the cavern, thus forming the broad cavern roof. With increasing dissolution, the fresh water becomes denser and sinks toward the base of the cavern.

Brining operations favor leaching by reverse circulation because operating costs are lessened as only the densest brines are produced at the base of the cavern. Less wash water is required per volume of produced brine than for direct circulation, which typically produces brines that are less dense. Careful blanket control is often used to shape the flat roof into the arch. This process adds stability and lessens the probability of roof caving.

Modified Circulation

Caverns may also be mined with <u>modified circulation</u> in which leach conditions are modified during the formation of the cavern. For instance, a sump may be formed by direct circulation; then the rest of the cavern is formed by reverse circulation by raising the wash casing and reversing the position of the fresh-water injection and brine return. Similarly,











Figure 7. Evolution of brine and storage caverns, Pierce Junction salt dome (after Minihan and Querio, 1973).

changes in the use of a cavern may dictate modifications in the leach technique. Figure 7 shows a cavern that initially was a brine cavern and then was used simultaneously for brine production and product storage (Minihan and Querio, 1973). Clearly, by varying the positions of the blanket strings and wash tubing and switching injection and return points, new cavern geometries were created that facilitated new uses of the dome.

CAVERN FAILURES

At least 10 solution caverns in Texas salt domes have failed. Failure is here defined as the loss of integrity of an individual cavern. Storage caverns (in contrast to brine caverns) have also failed in salt domes in Louisiana and Mississippi (Science Applications, Inc., 1977). The consequences of failure of a storage cavern are much greater than failure of a brine production cavern because of the value of the product that is lost and the cost of abatement procedures. Brine caverns show a much greater failure rate than do storage caverns. However, many brine caverns have been converted to storage caverns. Thus, any consideration of the stability of storage caverns must include brine caverns as well.

Three types of known cavern failures in Texas include (1) loss of stored products, (2) surface collapse, and (3) cavern coalescence. Table 1 lists cavern failures, possible mechanisms, and consequences.

There are approximately 254 caverns in Texas salt domes. On the basis of failure of 10 modern caverns (post-1946), the probability (p) of failure of a given cavern is approximately 4 percent (p=0.039). Statistics based on the years of cavern operation also yield indications of the useful life of a cavern. Railroad Commission of Texas permits indicate that the 254 Texas caverns have a cumulative operational history of 4,717 cavern-years. With 10 failures, the average operational life of an individual cavern is 472 years.

Two cavern failures in Texas salt domes resulted in catastrophic loss of liquid petroleum gas (LPG) at Barbers Hill salt dome in 1980 and at Blue Ridge salt dome in 1974. The failure of a storage cavern at Barbers Hill salt dome released LPG into subsurface formations below the

Failure mechanism	Dome	Storage cavern	Brine-well cavern	Rock-salt mine	Comments
Closure	Eminence salt dome, Mississippi	Natural gas storage cavern			Eminence salt domevery deep cavern, depth 5,700 to 6,700 ft; cavern closure up to 40 percent in first year; cavern bottom rose 120 ft; closure related to rapid pressure declines used to produce natural gas (i.e., cavern is operated "dry" without brine).
			No datacreep closure probably common		
				Minor problem with creep-related clo- sure and creep rup- ture of walls and roof	
Loss of integrity	Barbers Hill salt dome, Texas	LPG storage cavern			Barbers Hill salt domecatastrophic loss of LPG in 1980; LPG lost to subsurface formations, and at surface over dome; town of Mount Belvieu evacuated; problem inferred to be casing seat failure.
	Blue Ridge salt dome, Texas	LPG storage cavern			Blue Ridge salt domecatastrophic loss of LPG in 1974; LPG lost to subsurface formations and at surface over dome; minor flash fireexplosion injured 4 workmen during utility construction; RRC ordered cavern plugged and abandoned.
	· · · · · · · · · · · · · · · · · · ·		Common		
				Not applicable	

Table 1. List of salt domes with cavern failures, mechanisms, and consequences.

Coalescence	Pierce Junction salt dome, Texas	5 LPG storage caverns comprise 2 multicavern systems			Pierce Junction salt dometiming of coalescence is not known; caverns previously were brine producers; caverns currently used for LPG storage.
	Bayou Choctaw salt dome, Louisiana		3 brine caverns coalesced		Caverns abandoned.
	Sulfur Mines salt dome, Louisiana		3 brine caverns coalesced		Caverns abandoned.
				Not applicable	
Surface collapse	Palestine salt doine, Texas		16 collapse structures at surface over dome		Historic brine-well operations from 1904- 1937 resulted in very common surface collapse over old brine wells; 3 collapse structures formed since 1937.
	Grand Saline salt dome, Texas		L collapse structure		Collapse occurred in 1976 over probable brine well.
	Blue Ridge salt dome, Texas		i collapse structure		Collapse occurred in 1949 at brine well that formerly was a rock-salt mine.
	Bayou Choctaw salt dome, Louisiana		I collapse structure		Collapse occurred in 1954 over brine well; water-filled sinkhole.
	Jefferson Island salt dome, Louisiana			Major disaster mine flooded and abandoned	Oil-drilling rig probably breached mine opening; Lake Peigneur flooded into mine; disaster occurred 1980.

Table 1. List of salt domes with cavern failures, mechanisms, and consequences (cont.).

	Belle Island salt dome, Louisiana		Major disaster mine flooded and abandoned	Water leak around mine shaft resulted in surface collapse in 1973.
Other	Winnfield salt dome, Louisiana		Major disaster mine flooded and abandoned	Water leak issuing from mine wall flooded mine in 1965; water sand at cap-rock-salt- stock interface is inferred source of water.

Table 1. List of salt domes with cavern failures, mechanisms, and consequences (cont.).

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city of Mount Belvieu (Underground Resource Management, 1982), causing evacuation of the residents. The Warren Petroleum Co. assumed financial responsibility for the abatement and monitoring program. Over 400 shallow relief wells were drilled to vent the escaped LPG (Underground Resource Management, 1982). Although the Warren Petroleum Co. has not made public the cause of the leak, a failure in the casing seat is suspected. The defective cavern has since been returned to service after remedial work on the casing resulted in a successful integrity test.

Failure of a storage cavern at Blue Ridge salt dome also resulted in the escape of LPG. Four workmen installing a utility conduit were injured in an explosion and flash fire suspected to have been caused by leaking LPG. At that time, the cavern was owned by Amoco and used by Coastal States to store LPG. In 1975 the Railroad Commission of Texas issued special order 03-64,673, rescinding the authority to store LPG in that cavern (RRC Authority Number 03-34,658). That cavern is now abandoned. Figure 8 is a cross section of the upper part of Blue Ridge salt dome showing dome shape and the location and geometry of the salt mine and cavern.

Failure of brine caverns at Grand Saline, Blue Ridge, and Palestine salt domes have caused localized surface collapse. Sixteen collapse structures mar the surface above Palestine salt dome and are attributed to historic brine production (Fogg and Kreitler, 1980). The brine caverns that collapsed at Palestine salt dome have not been included in the statistics of cavern failures because those caverns were constructed with no regard for their stability, and construction techniques pre-date modern practices beginning in the late 1940's and 1950's.

From 1904 to 1937, Palestine Salt and Coal Company used brine wells to produce salt from Palestine salt dome. The collapse structures form circular water-filled depressions with diameters of 27 to 105 ft and depths of 2 to 15 ft (Fogg and Kreitler, 1980). Each collapse structure is assumed to mark the location of a former brine well. Powers (1926) described the brine operation as follows: Wells were drilled 100 to 250 ft into salt. Water from the "water sand" between the cap rock and the salt stock flowed into the well, dissolved the salt, and brine



Figure 8. Cross section of Blue Ridge salt dome showing geometry of salt mine and storage cavern that failed.

was then displaced by compressed air. The cap rock was undermined by the large brine cavern below it. The cap rock eventually collapsed forming a large sinkhole (Hopkins, 1917). A new brine well was simply offset a safe distance. Although brining operations ceased in 1937, three collapsed structures have formed since 1978 (Fogg and Kreitler, 1980).

In 1975, a circular collapse structure formed at Grand Saline, Texas. Although the exact origin in unknown, the collapse structure is inferred to overlie an old brine production well (Martinez and others, 1976; Science Applications, Inc., 1977). In 1949, a spectacular collapse occurred at Blue Ridge salt dome (Science Applications, Inc., 1977). An old rock-salt mine operated by Gulf Salt Co. had been converted into a brine production well. Without warning, the main building and well assembly collapsed around the original mine shaft and well bore. The brine cavern is inferred to have dissolved to the cap rock. A "water sand" composed of loose anhydrite grains at the cap-rock – salt-stock interface may have contributed water to help undermine the cap rock. The cap rock and overlying strata then collapsed into the brine cavity after removal of too much underlying support.

Railroad Commission of Texas records (Authority Number 03-60,093) indicate that five former brine caverns at Pierce Junction salt dome have coalesced to form two independent caverns. These caverns currently are used as storage caverns. When the caverns coalesced is unknown. Although five individual caverns have coalesced, integrity within each of the two multicavern systems has been maintained.

Conspicuous examples of cavern failures and surface collapses have been reported in Louisiana and Mississippi (Science Applications, Inc., 1977; Griswold, 1981; Fenix and Scisson, 1976b). One brine cavern has collapsed and formed a water-filled sinkhole at the surface over Bayou Choctaw salt dome (Science Applications, Inc., 1977). Two other caverns at Bayou Choctaw are abandoned because the caverns have dissolved to the cap rock. Three additional caverns, separated by at least 200 ft of pillar salt in plan, are now hydraulically connected (Griswold, 1981; Fenix and Scisson, 1976b). Rock-salt mines have also failed by flooding at Winnfield, Avery Island, and Jefferson Island salt domes. A jet of water issuing from a mine

wall caused the flooding and abandonment of Winnfield mine in 1965 (Martinez and others, 1976).

The Jefferson Island disaster of 1980 is an instructive example of the consequences of possible inadvertent breach into a mined opening in salt (Autin, 1984). Diamond Salt Company was operating a rock salt mine at Jefferson Island salt dome when a Texaco oil exploration rig (spudded from a barge in Lake Peigneur) was searching for flank oil production in sandstone pinch-outs near the salt stock. The chain of events that led to the draining of Lake Peigneur into the salt mine is paraphrased here on the basis of a description of the event by Autin (1984).

During the morning of the disaster, the Texaco drill bit became stuck in the hole at a depth of 1,245 ft, and mud circulation was lost. Efforts to free the bit and reestablish mud circulation failed. The drill rig began to tilt and rapidly overturned. Within 3 hours the drill rig, the support barge, and Lake Peigneur all disappeared down into a rapidly developing sinkhole. At approximately the same time, the 1,300-ft-level of the mine was flooded. All mine personnel were evacuated safely.

Mechanisms of Cavern Failure

Most cavern failures result from integrity loss at the casing seat. Cavern coalescence is another common mode of cavern failure, especially with brine caverns. The casing system is vulnerable at zones of lost circulation during cavern construction and during product cycling. Clearly, the cemented zone, production tubing, and casing strings are the weak link in any cavern system because many problems that begin there can quickly evolve into severe problems, including eventual cavern collapse.

Blanket control protects salt from being dissolved behind the casing seat. This dissolution, if left unchecked, can lead to loss of the casing seat, loss of tubing, and eventual cavern collapse.

Another point of attack on the integrity of a cavern system is within the cap rock. The cap rocks of many salt domes are characterized by lost-circulation zones. These zones compose vuggy areas with open caverns up to tens of feet in vertical extent. The vuggy zones are concentrated in the transition and anhydrite zones of the cap rock. Many cap rocks also contain

a zone of loose anhydrite sand at the cap-rock – salt-stock interface. Presence of this zone at the cap-rock – salt-stock interface is critical because it indicates active salt dissolution with the accumulation of loose anhydrite sand as a residuum and the presence of an active brinecirculation system.

Lost-circulation zones weaken the integrity of any cavern system in two ways. During drilling, the difficulty of maintaining mud circulation forces the use of many circulation-control measures. Drilling may continue "blind," that is without mud returns, until salt is encountered. Then a temporary liner is set through the lost-circulation zone. Alternatively, cement may be pumped down the tubing to plug the lost-circulation zone. The cement is then drilled out, and if circulation is lost again the process is repeated until circulation is reestablished.

Even with modern drilling techniques, lost-circulation zones can cause problems severe enough to force hole abandonment. In 1974, a hole was lost while drilling a gas-storage well at Bethel salt dome (RRC Authority Number 06-05,840). Circulation was lost within the cap rock and was not reestablished even though 1,300 sacks and 80 yd³ of cement were added. Ground subsidence then caused the rig to tilt, and the hole was abandoned.

Vuggy zones in cap rock are areas of natural cap-rock and salt dissolution. Therefore cement-formation bonds are vulnerable to attack by natural dissolution. The natural brinecirculation system also may attack the cement itself and reduce its useful life. The brine is very corrosive, and its long-term effects on cements and casings are inadequately known.

Van Fossan (1979) has listed various mechanisms whereby product loss may occur through loss of cavern integrity.

SALT-DOME RESOURCES

Valuable natural resources are associated with the salt stock, cap rock, and favorable geological structures and reservoirs associated with the growth and emplacement of the dome. Dome salt is an important chemical feedstock. Salt is extracted both by underground mines and by solution-brine wells. Storage space, available in cavities formed by brining operations, was

initially an unrecognized resource, but now many cavities in domes are created exclusively for storage space and the brine is discarded. The cap rock is quarried as a source of road metal, and cap-rock sulfur is mined by the Frasch process. Petroleum in salt-dome-related traps is by far the most valuable salt-dome-related resource.

The long-term trends for petroleum and sulfur production are in decline owing to depleted reserves and few new discoveries. Salt production is stable to slightly growing, but production is constrained by demand. Demand for storage space is growing rapidly especially with the requirements of the Strategic Petroleum Reserve (Fenix and Scisson, 1976b, c, d; U.S. Federal Energy Administration, 1977a, b, c; Hart and others, 1981). Conceivably, the storage space within a dome may be the most valuable salt-dome-related resource.

Salt-Dome Storage

Texas is the national leader in storage capacity for hydrocarbons in salt domes. In 1983, Texas salt domes housed 47 percent of the nation's total stored light hydrocarbons (liquified petroleum gas, or LPG). Texas salt domes are also becoming a major repository for the Strategic Petroleum Reserve (SPR) (fig. 9). Crude oil for the SPR is currently being stored at Bryan Mound salt dome, and additional storage capacity is under construction at Big Hill salt dome (Hart and others, 1981). Storage of toxic-chemical waste in solution-mined caverns is also being considered at Boling salt dome (United Resource Recovery, 1983).

The most common hydrocarbons stored in Texas salt domes are light hydrocarbons, natural gas, and crude oil. Rarely fuel oil may be stored near a plant to generate power during a gas curtailment. Light hydrocarbons, such as ethane, propane, butane, and isobutane, comprise the bulk of stored products. They are gases under atmospheric pressure and room temperature, but are liquids under the slight confining pressure. Light hydrocarbons were the first products stored in salt-dome caverns because the demand for the products was strongly cyclical with the seasons. In 1983, approximately 219,464,000 barrels of light hydrocarbons were stored in Texas



Figure 9. Histogram of 1983 storage capacity in Texas salt domes and proposed Strategic Petroleum Reserve caverns.
salt domes (Gas Processors Association, 1983). Of the total storage capacity in Texas for light hydrocarbons, 77 percent is in salt domes, and the remainder is in bedded salt in West Texas.

Whether a dome is a good candidate for storage is typically determined by its location near industrial suppliers and pipelines. Geologic characterization of candidate domes was done primarily to obtain site information for casing details. Geologic deficiencies such as small dome size and cap-rock-lost-circulation zones were viewed as minor engineering problems to be dealt with and not as site selection criteria. Figure 10 shows domes with active, abandoned, and pending storage facilities. Table 2 is a list of pertinent information on the domes with a history of hydrocarbon storage.

Barbers Hill salt dome houses the greatest concentration of storage facilities in the world. Nine separate companies store light hydrocarbons in the dome. The 1983 capacity for light hydrocarbons storage at Barbers Hill salt dome was 155,522,000 barrels (Gas Processors Association, 1983). There are approximately 137 caverns in Barbers Hill salt dome.

Congress in 1975 passed the Energy Policy and Conservation Act, which established the Strategic Petroleum Reserve to protect the nation against future oil supply interruptions. The size of the reserve was expanded to I billion barrels by President Carter's National Energy Plan. Crude oil for the SPR is currently being stored in preexisting brine caverns at Bryan Mound salt dome, and new caverns are being constructed at Big Hill salt dome.

Present capacity at Bryan Mound salt dome is 56.8 million barrels in four caverns originally mined for brine. Figures 11 and 12 are cross sections of the dome showing the geometries and locations of the caverns. Their irregular shape is typical of caverns originally mined for brine. Projections include construction of an additional 120 million barrels of storage space at Bryan Mound salt dome. Cavern construction for the SPR is underway at Big Hill salt dome. Fourteen caverns will be constructed, each with a capacity of 10 million barrels. Figures 13 and 14 are cross sections showing the proposed geometries and locations of the SPR caverns at Big Hill salt dome and the location and geometry of a storage cavern used by Union Oil Co, to store light hydrocarbons.



HYDROCARBON STORAGE IN SALT DOMES OF TEXAS

Figure 10. Map of salt domes showing active, abandoned, and pending storage facilities.

(continued)

Figure 10 (cont.).

Code	Dome Name
88	Barbers Hill
8E	Bethei
BI	Big Hill
BL	Blue Ridge
BO	Boling
BR	Brenham
вм	Bryan Mound
BT	Butler
СМ	Clemens
DA	Day
ET	East Tyler
FN	Fannett
HA	Hainesviile
HU	Hull
MK	Markham
MB	Moss Bluff
ND	North Dayton
PJ	Pierce Junction
SO	Sour Lake
SR	Stratton Ridge

County

Chambers Anderson Jefferson Fort Bend Wharton/Fort Bend Austin/Washington Brazoria Freestone Brazoria Madison Smith Jefferson Wood Liberty Matagorda Chambers/Liberty Liberty Harris Hardin Brazoria



Figure 11. Cross section of Bryan Mound salt dome (north-south) showing geometry of present Strategic Petroleum Reserve caverns.



Figure 12. Cross section of Bryan Mound salt dome (east-west) showing geometry of present and proposed Strategic Petroleum Reserve caverns.



Figure 13. Cross section of Big Hill salt dome (north-south) showing geometry of proposed Strategic Petroleum Reserve caverns and Union Oil Co. storage cavern



Figure 14. Cross section of Big Hill salt dome (east-west) showing geometry of proposed Strategic Petroleum Reserve caverns.

Table 2. List of salt domes with storage, operating company, Railroad Commission of Texas applicant, number of caverns, capacity, and product stored.

NAME OF SALT ODME	CURRENT OPERATOR OF STORAGE FACILITIES	Original Applicant	NUMBER OF CAVERNS	STORAGE CAPACITY IN BARRELS	PRODUCT STORED
NAME OF SALT DOME * RARBERS HILL * BARBERS H	CURRENT OPERATOR OF STORAGE FACILITIES TEXAS EASTERN DIAMOND SHANROCK WAREN X-ROL TENNECJ EXXON ENTERPRISE CONOCO ARCD BI-STONE FUEL UNION DEPARTMENT OF ENERGY ABANDONED VALERO SEMINOLE PIPELINE CO. DEPARTMENT OF ENERGY U.P.G. PHILLIPS PETROLEUM MBANDONED TEXAS EASTMAN WAREN PETROLEUM BUTANE SUPPLIES MOBIL TEXAS BRINE SENDRIFT PIPELINE MOSS BLIFF STORAGE VENTURE ENERGY STORAGE TERMINAL INC.	ORIGINAL APPLICANT TEXAS NATURYL GASOLINE DIAMOND SHAWROCK WARREN X-RAL TENNESSEE GAS TRANSMISSION HUMPLE OIL AND REFINING ENTERPRISE CONCO TEXAS BUTADIENE AND CHEMICAL CORP. BI-STOME FUEL PURE OIL CO. DEPARTMENT OF EMERGY TULOPA-AMOCO LO-VACA GATERING CO. SEMINOLE PIPELINE CO. ION CHEMICAL DEPARTMENT OF EMERGY FREESTONE UNDERGROUND STOR. PHILLIPS PETROLEUM GULF OIL WARREN PETROLEUM GAS CORP. MAGNOLIA PETROLEUM GAS CORP. MAGNOLIA PETROLEUM GAS CORP. MAGNOLIA PETROLEUM CORP. TEXAS BRINE- SENDRIFT PIPELINE MOSS RLUFF STORAGE VENTURE EMERGY STORAGE TERMINAL INC.	MUNBER OF CAVERNS 27 10 29 16 13 14 3 14 3 14 12 14 12 14 12 14 15 16 15 14 12 14 12 14 15 16 10 29 16 18 19 10 10 29 16 10 29 16 18 19 10 10 29 16 10 29 16 10 29 16 10 29 16 10 29 16 10 29 16 10 29 16 10 29 16 18 19 14 10 29 14 10 29 14 10 29 14 10 29 14 10 29 14 10 29 14 10 29 14 10 29 14 10 29 14 10 29 14 10 20 14 10 20 14 10 20 14 10 20 14 10 20 10 10 20 10 10 20 10 10 20 10 10 20 10 10 20 10 10 20 10 10 20 14 10 20 10 10 10 10 10 10 10 10 10 1	STORAGE CAPACITY IN BARRELS 30973000 34700000 45032000 22045000 3710000 1200000 4914000 9000000 4914000 9000000 4914000 9000000 4900000 4900000 4900000 56300000 4900000 4900000 2428000 1742000 3630000 1900000 0 4900000 0 0 4900000 0 0 4900000 0 0 0	PRODUCT STORED LIGHT HYDROCARBONS LIGHT HYDROCARBONS LIGHT HYDROCARBONS LIGHT HYDROCARBONS LIGHT HYDROCARBONS LIGHT HYDROCARBONS LIGHT HYDROCARBONS LIGHT HYDROCARBONS CRUDE OIL LIGHT HYDROCARBONS CRUDE OIL LIGHT HYDROCARBONS CRUDE OIL LIGHT HYDROCARBONS LIGHT HYDROCARBONS
- PIERCE JUNCTION - SOUR LAKE - STRATTON RIDGE - STRATTON RIDGE - STRATTON RIDGE	CUASTAL STATES CRUDE GATHERING TEXACO SERINGLE PIPELINE AMOCO DOM	ILLASTAL STATES CRUDE GATHERING THE TEXAS CO. SEMINOLE PIPELINE FENIX AND SCISSON DOW	7 3 4 7 9	12734000 1196000 152000 5257000 7000000	LIGHT HYDROCARBONS LIGHT HYDROCARBONS LIGHT HYDROCARBONS LIGHT HYDROCARBONS
			<u></u>	,000000	

LIST/TITLE L(18) NAME OF SALT DOME, 8(1), R(30) CURRENT OPERATOR OF + LIST/TITLE L(18) NAME OF SALI DOME, 8(1), R(30) CURRENT OPERATOR OF + STORAGE FACILITIES , 8(1), R(26) ORIGINAL APPLICANT , 8(1), STORAGE FACILITIES , 8(1), R(36) ORIGINAL APPLICANT , 8(1), R(7) NUMBER +OF +CAVERNS, 8(1), R(10) STORAGE +CAPACITY +IN BARRELS, 8(3), R(7) NUMBER +OF +CAVERNS, 8(1), R(10) STORAGE +CAPACITY +IN BARRELS, 8(3), R(7) NUMBER +OF +CAVERNS, 8(1), R(10) STORAGE +CAPACITY +IN BARRELS, 8(3), R(7) NUMBER +OF +CAVERNS, 8(1), R(10) STORAGE +CAPACITY +IN BARRELS, 8(3), R(18) PRODUCT STORED /C1, C226, C227, C229, C236, OB LOW C1 WH C226 EXISTS: R(18) PRODUCT STORED /C1, C226, C227, C229, C236, OB LOW C1 WH C226 EXISTS:

Two domes in Texas--Bethel and Boling salt domes--store natural gas. Natural gas is significantly different from other products stored in salt domes because of its high pressures during storage and rapid pressure declines during production. At Bethel salt dome, natural gas is stored in caverns under a cavern-storage pressure of 3,500 pounds per square inch gauged (psig). The depth of the cavern is between 4,300 and 4,800 ft.

Boling salt dome is a good example of a salt dome with multiple use of the available resources (fig. 15). Oil is produced from oil fields over the cap rock, within the cap rock, and from flank reservoirs. Boling salt dome has been the world's largest single source of sulfur. Valero Gas Co. has recently expanded its natural-gas storage facility at Boling to four caverns.

A cross section of Boling salt dome shows the geometry of the upper part of the salt dome illustrating cap rock, sulfur production, the location and size of two Valero storage caverns, and the proposed locations of a field of toxic-chemical waste caverns by United Resource Recovery, Inc. (fig. 16). Several aspects are important. The Valero caverns are located about 10,000 ft from the Texas Gulf Sulfur producing zone. Despite the 10,000 ft of separation, however, during construction of the Valero storage cavern no. 3, problems occurred that apparently are directly related to sulfur production. The well encountered, within the cap rock, a zone bearing high-pressure "mine waters" that caused the well to "kick." Texas Gulf Sulfur personnel were needed to cap the well. Although there is a large separation between the sulfur-mining operations and the active and proposed storage operations, the impact of the sulfur-mining operation extends far across the salt dome. Additionally, the proposed toxic-waste caverns are located near the periphery of the dome. Characteristically the internal constituents of salt domes--anhydrite and other country rock--increase toward the margins of salt stocks.

Salt Resources

Texas salt domes constitute an immense reservoir of salt that has risen through gravity deformation from great depths to lie within man's reach. Salt is a major industrial commodity that is used as a chemical feedstock, for road deicing, and for human and animal consumption.



Figure 15. Map of Boling salt dome showing locations of oil fields, sulfur production, Valero Gas Co. gas-storage caverns, and United Resource Recovery, Inc., lease area (modified from Galloway and others, 1983).



Figure 16. Cross section of Boling salt dome (east-west) showing location of sulfur production, geometry of Valero Gas Co. gas storage caverns, and proposed location and geometry of United Resource Recovery, Inc., waste-storage caverns.

Salt is produced from Texas salt domes by conventional underground mining and by solutionbrine wells. Estimates indicate that salt reserves will be adequate for 381 years (Griswold, 1981) to 26,000 (Hawkins and Jirik, 1966). The smaller figure is more reasonable on the basis of less recoverable salt at shallower depth, growth in salt demand, and preemption of some domes by storage requirements. Figure 17 shows those domes with active rock-salt mines and brine operations. Table 3 lists pertinent information on the operations at those domes.

Rock-Salt Mine

Currently, two active underground salt mines exist in Texas salt domes, the Kleer mine at Grand Saline salt dome and the United Salt mine at Hockley salt dome. According to Science Applications, Inc. (1977), Blue Ridge salt dome also housed a rock-salt mine that was later converted to a solution-brine mine. The well and mine opening collapsed in 1949. Both the Hockley and the Grand Saline salt mines are relatively small, and the operations are constrained by demand. Production is from one level in each of the mines. The primary use for the mined granulated and compressed rock salt is as a dietary supplement for animals (that is, salt lick).

Solution-Brine Well

Solution-brine wells for the production of chemical feedstock are active at seven salt domes in Texas including Barbers Hill, Blue Ridge, Markham, Palangana, Pierce Junction, Spindletop, and Stratton Ridge salt domes. Historically, the Indians first used natural brines from East Texas salt domes as a source of salt and brine for tanning hides. In the past, salt caverns, which were created as the brine was produced, constituted an unrecognized resource. Many brine caverns have been converted to store light hydrocarbons. Currently, the DOE is using four large storage caverns in Bryan Mound salt dome, created by Dow Chemical Co. during past brining operations, for crude-oil storage in the SPR. The present capacity of the former brine caverns at Bryan Mound is 56.8 million barrels.



SALT RESOURCES FROM SALT DOMES OF TEXAS

Figure 17. Map of salt domes showing active rock-salt mines and solution-brine wells.

Table 3. List of salt domes with salt production, method, status, company, and history.

NAME OF SALT DOME	HINERAL	STATUS OF PRODUCTION	REPORTING ORGANAZATION OR MINING METHOD	NAVE OF COMPANY	MINING HISTORY
* BARBERS HILL * BLUE RIDGE	BRINE	ACTIVE. ACTIVE	BRINE WELLS BRINE WELLS	DIAMOND SHAMROCK UNITED SALT	
* BLUE RIDGE * BROOKS DOME * BRYAN MOLIND	ROCK SALT BRINE BRINE	ABANDONED ABANDONED ABANDONED	SALT MINE L.S.U1976 BRINE HELLS	UNITED SALT UNKHOUH DOW_CHEMICAL	1865
* GRAND SALINE DOME * GRAND SALINE DOME * HOCKLEY	ROCK SALT BRINE ROCK_SALT	ACTIVE ABANDONED ACTIVE	SALT MINE BRINE KELLS SALT MINE	MURTON SALT MORTON SALT UNITED SALT	1845 192 9- PRESENT
* MARKHAM * PALIYAGANA DOME * PALESTINE DOME	BRINE BRINE BRINE	ACTIVE ACTIVE ABANDONED	BRINE WELLS BRINE WELLS L.S.U <u>19</u> 76	IEXAS BRINE CURP. P.P.G.IND.INC. UNKNOWN	1865
* PIERCE JUNCTION * SPINDLETOP * STEEN DOME	BRINE BRINE BRINE	ACTIVE ACTIVE ABANDONED	BRINE WELLS BRINE WELLS L.S.U1976	TEXAS BRINE CORP. TEXAS BRINE CORP. UNKNOWN	1365
* STRATTON RIDGE * WHITEHOUSE DOME	BRINE BRINE	ACTIVE	BRINE WELLS L.S.U1975	doh (Hemical Unkno un	

LIST/THTELLISINGE E SALT DOFE SALA DOFE SALA PARENE SALA SALA

STATUS OF +PRODUCTION, 8(4), R(22) REPORTING ORGANAZATION+ STATUS OF +PRODUCTION, 8(4), R(22) REPORTING ORGANAZATION+

OR MINING METHOD , B(4), R(18) NAME OF COMPANY , B(4), R(14) MINING HISTORY/ OR MINING METHOD , B(4), R(13) HAME OF COMPANY , B(4), R(14) MINING HISTORY/

C1, C199, C200, C201, C202, C203, 08 LOW C1 WH C199 E0 ROCK SALT OR C199 E0 BRINE: C1, C199, C200, C201, C202, C203, 03 LOW C1 WH C199 E0 ROCK SALT OR C199 E0 BRINE:

Petroleum Resources

Oil discovered in 1901 at Spindletop salt dome gave birth to the modern petrochemical industry. The petroleum production of many Gulf Coast salt domes is truly staggering. Cumulative production from the salt-dome-related oil reservoirs (those greater than 10 million barrels cumulative production) is 3.46 billion barrels (Galloway and others, 1983). Oil is not found in the salt stock but in surrounding strata. Intrusion of the salt diapir can form a wide range of structural and stratigraphic traps for petroleum. Highly productive zones around salt domes include cap rocks, dome flanks, and supradomal crests.

An oil play is an assemblage of geologically similar reservoirs exhibiting similar trapping mechanisms, reservoir rocks, and source rocks (Galloway and others, 1983). Four major oil plays are associated with Gulf Coast salt domes. They include cap rock, Yegua salt-dome flanks, Yegua deep-salt-dome crests, and Frio deep-salt-dome crests.

This discussion of petroleum resources associated with salt domes centers on diapirs in the highly productive Gulf Coast (Houston Salt Basin) of Texas. Shallow piercement oil fields will be discussed generally, and then specific examples of the major oil plays associated with salt domes will be discussed in turn. Much of this discussion is based on two sources: a recent publication by Galloway and others (1983), which has proved to be a valuable guide to oil in Texas, and a book by Halbouty (1979), which is the standard oil-related salt-dome text.

Shallow Salt-Dome Oil Fields

Shallow salt-dome fields were the first oil fields discovered in the Gulf Coast area. Many fields discovered 70 and 80 years ago are still producing. This productive longevity stems in part from diapirism and faulting, which segmented reservoirs thus creating a diverse range of traps at many different stratigraphic levels. The yearly oil production of Spindletop salt dome illustrates that production has been prolonged and periodically increased dramatically by discovery of new types of salt dome traps (fig. 18).



YEARLY SPINDLETOP OIL PRODUCTION



Shallow-piercement-salt domes with cumulative oil production greater than 10 million barrels are located on figure 19. These domal fields are listed in table 4 with discovery dates, depth to cap rock and salt, productive area, and production figures (Galloway and others, 1983). Most oil has been produced from traps in cap rock, in strata truncated or pinched out against dome flanks, and in strata arched over dome crests. Although some very shallow diapirs are highly productive, there is a correlation between greater depth of burial of the dome and greater oil production (fig. 20). According to statistics from Halbouty (1979), known salt domes with crests greater than 4,000 ft deep have approximately twice the cumulative production of domes with crests buried less than 4,000 ft (80 million barrels vs. 38 million barrels).

Strata of Eocene through Pliocene age host most of the production associated with Gulf Coast salt domes. The Wilcox Group and the Yegua, Frio, and Fleming Formations compose the host strata. Major reservoirs and trap types discussed below are cap rock, dome flank (Yegua), and deep-salt-dome crest (Yegua and Frio). Boling salt dome is a good example of a shallow piercement dome with a large number of oil fields (fig. 21). Production is from supradomal sands, cap rock, and flank traps in Miocene, <u>Heterostegina</u> Limestone, and Frio reservoirs. Cumulative production through 1981 is 35.7 million barrels.

Cap-Rock Reservoirs

Four of the oldest fields in the Gulf Coast area--Spindletop, Sour Lake, Batson, and Humble--produce oil from calcite cap rock overlying shallow piercement salt domes. A total of eight shallow Gulf Coast diapirs had significant oil production from their cap rock. Most cap rocks have been exploited and their oil exhausted. Minor cap-rock production from Day salt dome in Madison County, however, was initiated in 1981. The location of some cap-rock fields over Boling salt dome is shown in figure 21.

Cap-rock fields typically showed prolific initial production and then rapid production decline (fig. 17). Production is from microscopic to cavernous porosity. Porosity values up to 40 percent are reported (Galloway and others, 1983).



Figure 19. Map of piercement salt domes showing oil fields that have produced more than 10 million barrels of oil (after Galloway and others, 1983).

Figure 20. Graph showing depth to the crest of Texas salt domes and their cumulative oil production through 1975 (modified from Halbouty, 1979).





Figure 21. Map of Boling salt dome showing locations of oil fields (after Galloway and others, 1983).

	<u></u>	Tee	Тор		Pr	uduction	Cumulative	Estimated ultimate
field	Discovery date	сар (II)	الدی (ft)	Supradome	Cap	Flank	production (million barrels)	recovery (million barrels)
Destaur Little	1916	350	1 000	Ne	No	frio, Miocene	128.0	129.3
Damers (10)	1003	1 080	2 050	Miocene	Yes	Miocene, Frio, Yegua	60 6	61.0
Baison Bio Conste	1977	450	635	Miocene, Frío	No	Vicksburg	24.6	27.0
BLue Ridue	1919	143	230	No	No	Miocene, Frio, Vicksburg	24 1	24 3
Dulie Ruge	1975	383	975	Miocene	Yes	Miocene, Frio	35.7	36.2
Chun Lako	1917	505	A 173	Miocene	No	No	18.7	19.4
Clant Lake	1978	1 800	2,400	Wilcox, Sparta and Queen City	No	No	12.8	13.2
Damon Marrol	1915	i,000	529	No	No	frio, Miocene	21.6	21.9
Dushuru	1930	3011BCC	4.948	Miocene	No	Frio	21.6	21.9
Emorrow	1070	none	6 170	Miocene, Frio, Vicksburg	No	Yegua	50 5	51.9
Esperson	1927	741	2.080	Miocene?	No	Frio	51.0	52.9
Fannen Cupus Crook	1980	5 000	-,0==	Frio, Miocene	No	No	134.7	135.2
Clobe Creek	1979	7 5 15	7.582	Miocene, Frio	No	No	48.8	51.0
Markancy	1922	150	1.226	No	No	Miocene, Frio	132.0	134.2
1106111210110	1010	150	595	Να	Yes	Miocene, Frio, Yegua	183.5	185.9
tiuu Muodelu	1005	700	1 2 1 4	Pliocene, Miocene	Yes	Frio, Yegua	168.2	169.5
Liboro Couth	1975	275	460	No	Na	Miocene, Frio, Vicksburg, Yegua	86.1	88.0
Liberty Soom	1909	1 380	1 417	Miocene	Yes	Frio	17.6	17.7
Mone's Orthaut	1926	285	369	No	No	Miocene, Frio, Yegua	21.8	22.1
Oranna	1913	0000	7.120	Miocene, Frio	No	Hackberry	61.8	62.8
Pierce function	1971	630	860	No	No	Miocene, Frio, Vicksburg, Jackson, Yegua	68 3	U8.9
Post Machar	1928	0.00	6 948	Miocene, Frio	No	Hackberry	31.7	32.4
FULL PICERES	1901	1 500	1,900	Miocene	No	Yegua	59.2	61.1
Saurioga Sauriota	1907	000,1	719	Miocene	Yes	Frio, Jacksoni, Yegua	123.8	126.8
JOBT LAKE	10.01	000	1 200	Miocene	Yes	Miocene, Frio	153.2	153 9
aparenciop Mari Columbia	1904	650	768	No	Yes	Miocene, Frio	162.2	163 6
AAG24 COIDHUDIN	1001	010	700			·	1,922.1	1,952.1

Table 4. Lis	t of salt domes with	large oil fields and	production status.
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The genesis of cap rock is complex. Cap rock typically occurs at the crest of shallow piercement salt domes and may extend for some distance down the dome flanks. Mineralogically, most cap rocks are composed of a basal anhydrite zone, a middle gypsum or transition zone, and an upper calcite zone. The anhydrite is a dissolution residuum that accumulated as ground water dissolved anhydrite-bearing salt at the dome crest and flank. Gypsum then formed by hydration of anhydrite. Calcite is formed by sulfate reduction of gypsum with bacterial reaction with oil. The calcite zone is the typical oil reservoir in the cap rock.

Cap rocks are complex karstic features. They accumulated as a dissolution residuum and may themselves be undergoing dissolution. To this day, cap rocks are exceptionally difficult zones to complete and case a well through. Lost-circulation zones cause major problems involving mud circulation and complete cementation of casing strings. Active circulation of brine in cap-rock pores also provides a geochemical environment that is corrosive to casing and cements.

Some Gulf Coast cap rocks record evidence of erosion over the dome (Hanna, 1939). The cap rock of Orchard salt dome is thin over the dome crest but is up to 1,000 ft thick (stratigraphically) on the dome flanks (fig. 19). Pleistocene sands and gravels truncate Miocene strata around the dome periphery and apparently have stripped calcite cap rock from the dome crest.

Salt-Dome Flank Reservoirs

Important oil production from sandstones flanking salt domes was initiated at Spindletop dome in 1925 (Halbouty, 1979) (fig. 18). These flank reservoirs typically are thin sandstones steeply inclined upward toward the diapir flank. The sandstones may be truncated by the dome or pinch out toward the dome (fig. 22). Commonly, radial faults segment the sand bodies into discrete fault blocks.

Delta-front sheet sandstones of the Yegua Formation constitute the most important dome flank reservoir (Galloway and others, 1983). Major Yegua flank sands are reservoirs at Hull,



Esperson, and Saratoga salt domes. An example of the geometry of these flank sands and reservoirs is illustrated by Orchard (Moores Orchard) salt dome (fig. 22). The steep inclination of the flank sands makes them elusive targets, but this inclination also yields thick oil columns, efficient gravity segregation, and efficient water drives for impressive single-well production statistics.

Deep-Seated Dome Crest Reservoirs

Yegua and Frio sandstones arched over the crest of deep-seated salt domes produce the greatest cumulative amount of salt-dome-related oil in the Texas Gulf Coast (Galloway and others, 1983) (fig. 23). Most fields overlie known deep-seated salt domes such as Raccoon Bend (Yegua production) and Thompson, Manvel, Webster, and Cedar Point (Frio production). Other fields such as Katy may overlie non-piercing salt structures (Halbouty, 1979) or turtle-structure sediment-cored anticlines (Winker and others, 1983; Galloway and others, 1983).

Faults play a variable role in oil trapping and compartmentalization of reservoirs. For example, the Frio deep-seated dome crest trend is along the Vicksburg and Frio growth-fault trends. In contrast to the ubiquitous radial faults associated with shallow piercement salt domes, deeply buried salt domes normally have fewer associated faults as at Sugarland salt dome.

The average depth of reservoir rocks in the Yegua trend is approximately 5,000 ft. The reservoir sandstones are a complex of deltaic sand bodies including distal fluvial, distributarychannel-fill, and crevasse-splay facies (Galloway and others, 1983). The average depth of reservoir rocks in the deep Frio trend is approximately 6,000 ft. Reservoir rocks include a wide range of deltaic facies including delta-front, delta-margin, distributary-channel-fill, and destructional barrier facies (Galloway and others, 1983). The reservoir-drive mechanism is an efficient water drive commonly assisted by gas-cap expansion. Most of the larger fields are unitized with reservoir-wide secondary gas injection.





Petroleum Resources of Salt Domes in the East Texas and Rio Grande Basins

Oil production from East Texas and Rio Grande salt diapirs is much less than production from diapirs in the Houston Salt Basin (fig. 20). No fields around diapirs in the East Texas or the Rio Grande Basins have produced greater than 10 million barrels of oil. Shallow salt domes (less than 6,000 ft) have produced less than 1 percent of the oil from the central part of the East Texas Basin (Wood and Giles, 1982).

The East Texas Basin on the whole is an extraordinarily oil-rich basin. The East Texas oil field alone has produced 4.68 billion barrels of oil. Deeply buried non-piercing salt structures are highly productive in the East Texas Basin. Hawkins and Van salt structures have produced 734 million and 485 million barrels of oil, respectively. The question remains, why are diapirs in the interior basins so barren in comparison with coastal diapirs?

Several factors have acted to minimize the entrapment of oil in interior salt diapirs. Diapirs in interior basins have greater structural maturity than do coastal diapirs. This structural maturity is characterized by steep flanks of the diapir and a surrounding rim syncline. Most diapirs in the East Texas Basin are surrounded by strata that dip toward the diapir or are flat lying. In contrast, the flanks of many coastal diapirs are less steep, and strata typically are inclined upward toward the dome. The increased maturity of East Texas diapirs results in the structural closure being minimized around the domes.

The domes of the East Texas Basin are also much older than coastal diapirs. Most coastal domes probably became diapirs in the Oligocene or Miocene, 10 to 35 million years ago. In contrast, East Texas domes became diapirs from 80 to more than 112 million years ago (Seni and Jackson, 1983b). Thus, if large amounts of oil had accumulated over the crests of early pillows that later evolved into East Texas diapirs, the hydrocarbons would have had a long period of time to leak during dome uplift, during erosion of previously deposited strata over the dome crest, or both.

Sulfur Resources

Historically, a major proportion of the world supply of sulfur came from Texas salt domes. Sulfur production began in Texas at Bryan Mound salt dome. Sulfur has been produced commercially from the cap rocks of 15 Texas salt domes. Currently, Boling salt dome contains the only active cap-rock-sulfur mine in Texas (fig. 15). Texas cap-rock sulfur mining has declined owing to exhaustion of reserves, lack of new cap-rock discoveries, and price competition from sulfur produced by secondary recovery of sulfur from sour gas and petroleum refining.

This section will present the history and technology of sulfur mining and the geology of cap-rock sulfur deposits.

History and Technology

Sulfur was first discovered in 1867 in cap rock of coastal salt domes at Sulfur Mines salt dome in Louisiana. Louisiana Petroleum and Coal Oil Co. was searching for oil and instead discovered a thick deposit of native (free elemental) sulfur in cap rock at a depth of 650 ft. For 20 years, a number of ventures designed to mine the sulfur by underground methods failed. H. Frasch patented in 1890 a revolutionary sulfur-mining technology that is still used today with minor modifications. Basically the Frasch process uses hot water to melt the sulfur and compressed air to help lift the sulfur to the surface. Standard oil-field technologies are used to drill a hole to the base of the sulfur-bearing zone. Three stands of pipe are then set concentrically into the hole--the outer casing, the middle sulfur-production string, and the inner compressed-air line (fig. 24).

Casing (usually with diameter of 6 to 8 inches) is cemented into the hole. Two separate sets of perforations are made through the casing at the top and near the bottom of the sulfurbearing zone. According to Ellison (1971), the upper set of perforations is 8 to 10 ft above the base of the productive zone, and the lower set is 1 to 5 ft above the base. A ring-shaped seal is placed in the annulus between the sulfur-production string and the casing string between the



Figure 24. Casing string detail for cap-rock sulfur-production well (after Myers, 1968).

upper and lower sets of perforations. The seal prevents communication between the upper and the lower perforations within the annular space.

Superheated (300° to 325°F) and pressurized (125 to 100 psi) water is injected down the annulus between the casing and the sulfur-production string. The hot water exits through the upper set of perforations. The sulfur melts as the superheated water enters the sulfur-bearing zone. Molten sulfur is heavier than water and therefore sinks to the lower part of the sulfur-bearing zone. Pressure differentials drive the molten sulfur through the lower set of perforations into the casing. The seal forces the sulfur into the sulfur-production string. Compressed air at 500 to 600 psi is injected into the innermost compressed-air string. This helps force the sulfur to the surface by lowering the bulk density of the molten sulfur-air mixture.

Sulfur, having a purity of 99.5 percent, solidifies at the surface in large vats. Some operations directly ship the molten sulfur in insulated vessels.

Two ancillary operations during sulfur production involve recycling of the injected water and mitigating surface subsidence owing to sulfur removal. "Bleed-water" wells are drilled to produce and recycle excess water that was injected to melt the sulfur. Once the water has cooled below the melting point of sulfur, it must be recycled. By drilling "bleed-water" wells beyond the productive area, costs can be lowered and water flow is improved (Hawkins and Jirik, 1966).

Surface subsidence over areas of sulfur production is a problem common to many sulfurmining areas. The removal of sulfur opens a series of void spaces in the cap rock. The collapse of these voids causes the subsidence over the mining operations. The closing of voids is beneficial in that less water is needed to mine the remaining sulfur. Many sulfur operations now pump special muds into the zone where sulfur has been produced to fill the voids and prevent surface subsidence. A 2 mi² area over Boling salt dome has subsided up to 20 ft. An extensive system of levees protects the area from flooding. In addition to flooding, subsidence may cause damage to well bores, casing, and surface facilities.

Characteristics of Cap-Rock Sulfur Deposits

Native (free) sulfur has been reported in cap rock of 25 Texas salt domes. Fifteen of these domes have undergone commercial sulfur production (figs. 25 and 26). Only Boling salt dome has active sulfur production. Boling salt dome has been continuously active since 1929 (fig. 24) and is the world's largest single sulfur source. A cross section of Boling salt dome, its cap rock, and sulfur zone is shown in figure 27.

Cap rock is a particularly complex area of a salt dome. Cap-rock thickness ranges from a feather edge to more than 1,000 ft. Cap-rock depth ranges from above sea level to depths greater than 4,000 ft. Sulfur typically occupies vugular porosity at the base of the calcite zone. The thickness of the sulfur-bearing zone may exceed 300 ft. Sulfur is typically found on the outer periphery, or shoulder, of shallow piercement salt domes (fig. 28) (Myers, 1968). Some small domes have sulfur deposits across the entire crestal area. Even though the larger domes, such as Boling salt dome, have sulfur over only a portion of their crests, the larger domes have mineralization over a much larger area and generally of greater thicknesses. In the Gulf Coast area, the depth of sulfur mining is typically from 900 to 1,700 ft. Orchard salt dome exhibits the greatest depth of sulfur production at 3,200 ft.

Cap-Rock Resources

The cap rock hosts and also comprises most of the other resources associated with salt domes. The cap rock is an exceedingly complex environment as demonstrated by its variable stratigraphy including calcite, gypsum (transition), and anhydrite zones. In addition to the caprock petroleum and sulfur resources already discussed, some cap rocks of Texas domes contain uranium (Palangana salt dome), Mississippi Valley-type sulfide deposits (Hockley salt dome), and silver minerals (Hockley salt dome). The cap rock is a valuable commodity as crushed stone in the rock-poor coastal regions. Just as the caverns in salt domes were an unrecognized resource for a long time, lost-circulation zones have been converted into convenient disposal zones for brine leached from storage cavern projects.



п

Figure 25. Graph showing the chronology of sulfur mining in Texas salt domes (modified from Ellison, 1971).



FRASCH SULFUR FROM SALT DOMES OF TEXAS



(continued)

Figure 26 (cont.).

Code Dome Name

BС	Big Creek
80	Boling
BM	Bryan Mound
СМ	Clemens
DM	Damon Mound
FN	Fannett
GU	Gulf
н	High Island
НМ	Hoskins Mound
LΡ	Long Point
м8	Moss Bluff
NA	Nash
	140000
oc	Orchard
OC PA	Orchard Palangana
OC PA SP	Orchard Palangana Spindletop

County Fort Bend Wharton/Fort Bend Brazoria Brazoria Jefferson Matagorda Galveston Brazoria Fort Bend Chambers/Liberty Brazoria/Fort Bend Fort Bend Duval Jefferson



QA/2220

Figure 27. Cross section of Boling salt dome showing cap rock and zone of sulfur mineralization (after Myers, 1968).



Figure 28. Map of Texas salt domes showing area of sulfur mineralization.

Crushed Stone

Cap rock has been mined from conventional above-ground quarries at Gyp Hill and Damon Mound salt domes. Only the quarry at Damon Mound is currently active. Cap rock has also been exploited on a small scale by underground mining at Hockley salt dome. False-cap-rock, or mineralized supracap, sandstones are now quarried at Butler salt dome. Most of the cap rock is used as road metal and base fill.

Other Resources

Mississippi Valley-type sulfide deposits and uranium have been reported (Smith, 1970a, b) and locally have been explored for in Gulf Coast cap rocks (Price and others, 1983). There has been no commercial production, however. The recent recognition that cap rocks may host Mississippi Valley-type sulfide deposits has generated intense interest in cap-rock genesis and fluid flow around salt domes. Price and others (1983) reported extensive sulfide mineralization and local silver minerals from an annular zone around the periphery of the cap rock. They related the deposition of the sulfide minerals to reduction in the cap rock environment by petroleum and possibly by H_2S , and to periodic expulsion of deep-basin brines that were the mineralizing fluids. Smith (1970a, b) listed 18 Texas coastal domes for which occurrence of sulfide minerals had been reported. Table 5 lists such Texas salt domes, type of sulfide mineral, and documentation.
List of salt domes with sulfide mineral occurrences and documentation. Table 5.

NAME OF SALT DOME	NAME OF SULFIDE	PRODUCTION STATUS	DOCUMENTATION REFERENCE	MINING COMPANY
**** * BIG HILL * BLUE RIDGE * DOLING * FEROUSON CROSSING * GULF * GULF * GULF * GULF * GULF * GULF * HIGH ISLAND * HIGH ISLAND * HIGH ISLAND * HIGH ISLAND * HOCKLEY * OCCHARD * OCCHARD * PALANGANA DOME * PALANGANA DOME * PIERCE JUNCTION * SOUR LAKE * SOUR LAKE * SOUR LAKE * SOUR LAKE * SOUR LAKE * SOUR LAKE * SOUR LAKE	GALENA PYRITE SPHALERITE BARITE CELESTITE GALENA HAVERITE PYRITE HAVERITE HAVERITE HAVERITE ALABANDITE GALENA SPHALERITE SPH	UCULRRENCE UCULRRENCE	SMITH-1970. A. B- SMITH-1970. A	NA NA NA NA NA NA NA NA NA NA NA NA NA N

list/title 1(18)name of salt dome.b(3),r(15)nume of sulfide, LIST/TITLE L(18)NAME OF SALT DOME.B(3).R(15)NAME OF SULFIDE,

b(3),r(12)production +status ,b(3),r(25)documentation reference, B(3),R(12)PRODUCTION +STATUS ,B(3),R(25)DOCUMENTATION REFERENCE, b(3),r(20):mining_commpany /cl,c199,c200,c201,c202,ob_low_c1 B(3),R(20)'MINING_COMMPANY /C1,C199,C200,C201,C202,0B_LOW_C1

wh c200 eq exploration or c200 eq occurrence: WH C200 EQ EXPLORATION OR C200 EQ OCCURRENCE:

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Wood, D. H., and Giles, A. B., 1982, Hydrocarbon accumulation patterns in the East Texas salt dome province: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 82-6, 36 p. APPENDIX i: Texas salt domes: natural resources, storage caverns, and extraction technology.

Structure-contour maps of Texas salt domes. Heavy lines are salt structure contours; light lines are surface topographic contours.















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APPENDIX 2. Railroad Commission of Texas Authority Numbers for storage-well permits.

NAME OF SALT DOME	CURRENT OPERATOR OF STORAGE FACILLITY	ORIGINAL APPLICANT	RAILROAD COMMISSION AUTHORITY NUMBERS
+++			
+ BARPERS HILL * BARBERS HILL	Texas eastern Diamond Sharrock	TEXAS NATURAL GASOLINE DIAMOND SHANROCK	03-27865,03-40761,03-40760 03-59299
* BARBERS HILL	HARREN Y-PAI	HARREN	03-63536
* BARBERS HILL	TENNECO	TENNESSEE GAS_TRANSMISSION	03-33373,03-77018,03-77903,03-32960
* BARBERS HILL	EXION	HUMBLE OIL AND REFINING	03-45459,03-65222
* BARBERS HILL	COMOCO	CONOCO	03-63409,03-76800
* BARBERS HILL	ARCO	TEXAS BUTADIENE AND CHEMICAL CORP.	03-33063
* BIG HILL	UNION	PLRE OIL COL	03-34046+03-33628
+ BIG HILL	DEPARTMENT OF ENERGY	DEPARTMENT OF EMERGY	03-79466
+ BLUE KILDE. + BOLING	VALERO	LO-VACA GATERING CO.	03-73654
+ BRENHYN	SEMINOLE PIPELINE CO.	SENINOLE PIPELINE CO.	03-76656
* Sryan Muunu * Bryan Muund	DEPARTMENT OF ENERGY	DEPARTMENT OF ENERGY	03-67782 03-70337
+ BUTLER DOME	U.P.G.	FREESTONE UNDERGROUND STOR.	05-23215
* ULEMENS * DAY	ABANDANETI	PHILLIPS PERKULEUM	03-31930,03-32483
+ EAST TYLER	TEXAS EASTMAN	HARREN PETROLEUM	06-22995
* FHINELL * HAINESVILLE	BUTANE SUPPLIES	ENTERPRISE PETROLEUM GAS CORP.	03-23675,03-29703,03-30296,03-31943 06-23529
* HULL	NOBIL TEXAC PRIME	MAGNOLIA PETROLEUN CORP.	03-27136
* MARKHAM	SEADRIFT PIPELINE	SEADRIFT PIPELINE	03-45456
+ MOSS BLUFF	MOSS BLUFF STORAGE VENTURE	MOSS BLUFF STORAGE VENTURE	03-72099
* PIERCE JUNCTION	ENTERPRISE	NANDA PETROLEUM AND ELLIS TRANSPORT	03-33874+03-60093
* PIERCE JUNCTION	CUASTAL STATES CRUDE GATHERING	COASTAL STATES CRUDE GATHERING	03-26489,03-64779
* SUUR LAKE * STRATTON RIDGE	IERALU SEMINDLE PIPELINE	INE IEXAS CU. SEMINALE PIPELINE	03-75381,03-25803,03-30937,03-23476 03-76306
* STRATTON RIDGE	AHOCO	FENIX AND SCISSON	03-62057
* SIRATION RIDUE	LRJW	此 》	03-26779,03-45413,03-60633,03-60845;03-74630

LIST/TITLE L(17)NAME OF SALT DOME, R(1), R(30)CURRENT OPERATOR OF	+
LIST/TITLE L(17)NAME OF SALT DOME, B(1), R(30)CURRENT OPERATOR OF	+
STORAGE FACILITY ,B(1),R(35)ORIGINAL APPLICANT	,B(1),
STORAGE FACILITY ,B(1),R(35)ORIGINAL APPLICANT	,B(1),
R(48)RAILROAD COMMISSION AUTHORITY NUMBERS / R(48)RAILROAD COMMISSION AUTHORITY NUMBERS /	
C1,C226,C227,C230,OB LOW C1 WH C226 EXISTS: C1,C226,C227,C230,OB LOW C1 WH C226 EXISTS:	

APPENDIX 3. Railroad Commission of Texas Rule 74 procedures and requirements for storagewell operators.

ILLE YOLL WILLT	end a mar fule 74, adopted on tive on April 1, 1982. Interest Constant	
RAILROAD COMMISSION OF OIL AND GAS DIVISION	BOTTCE DF RULE AVENNE ccied (s an amendmant to Rules 9 and 46. 21, 1981. These rules vill become effec them Joint Underground	
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Railroad Commission of Texas Oil and Gas Division 051.02.074 051.02.02.074

(a) <u>Permit required</u>. No person may create, operate, or continue to use or maintain an underground hydrocarbon storage facility without obtaining a permit from the commission. Permits from the commission issued before the effective date of this rule shall continue in effect until revoked, modified. RULE 74. UNDERGROUND HYDROCARBON STORAGE. or suspended by the commission.

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(b) App)(cation.

mineralized water arising out of or incidental to the creation, operation, or mutintenance of the underground storage facility shall be filed with the (1) An application for a permit to dispose of seltwater or other commission in accordance with the appropriate commission rules. [2] An application for a permit to create, operate, or maintain an underground hydrocarbon storage facility shall be filed in the Austin office of the commission and shall contain the necessary information to demonstrate compliance with the laws of Texas and the rules of the commission. (c) Geplogical requirement.

(1) Underground hydrocarbon storage facilities shall only be created, operated, or maintained in formations which are confined by impervious strata so as to prevent the waste of hydrocarbons, the uncontrolied escape of hydrocarbons to the surface, and the escape of hydrocarbons into freshweter formations. (2) The applicant must submit a letter from the Texas Department of Water Resources, Austin. Texas, with the application, stating the depth to which freshwater strata occurs at each storage facility.

(d) Motice and hearing.

(1) The applicant shall give motice by mailing or delivering a copy of the application to the curface owner of the tract under which the

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Railroad Commission of Texas 011 and 6as Division 051.02.07.074

facility is located and to each adjuining officet operator, on or before the date the application is mailed to or filed with the commission.

the county where the facility will be located in a form approved by the applicant shall file in Austin proof of publication prior to the hearing or {2} Motice of the application shall be published by the applicant in three consecutive publications in a newspaper of general circulation for director of underground injection control (hereinafter "director"). The administrative approval. (3) An application for a new underground hydrocarbon storage project will be considered for approval only after notice and hearing. After hearing, the examiner shall recommend a final action by the commission. (4) An application for an expansion of a provioualy approved project may be considered for administrative approval if the commission receives no protest.

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be held on the application after the commission provides actice of hearing to (A) If the commission receives a protest from a person motified pursuant to paragraph (1) or other interested person within 15 days of receipt of the application or after publication that the proposed plan as contained in the application will cause damage to oil, gas, genthermal resources, freshwater resources, or otherwise cause harm, then a hearing will all interested persons.

administratively approve the application. If the director denies (B) If the commission receives no protest, the director may administrative approval, the applicant shall have a right to a hearing on the matter. After hearing, the examiner shall recommend a final action by the comission.

(e) <u>Subsequent commission action</u>. A permit may be modified, suspended.

or terminated atter notice and opportunity for hearing if:

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(1) A substantial change of conditions occurs in the operation, maintenance, or construction of the facility, or there are substantial changes in the information originally furnished;

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(2) freshwater is likely to be polluted as a result of continued operation of the facility;

(3) There are substantial violations of the terms and provisions of the permit or of commission rules;

(4) The applicant has misrepresented any material facts during the

Permit issuance process; or (5) injected fluids or gases are escaping from the storage

facility. (f) <u>irrafer</u>. An underground hydrocarbon storage permit may be

traniferred only upon written sproval. The permitted operator shall file an application with the director for approval of the transfer of the permit for P-4 the facility. The director any require a hearing on the matter. After hearing, the examiner shall recommend a final action by the commission.

(9) <u>Casing</u>. Wells used for injection and removal of hydrocarbons from the storage facility shall be cased and the casing strings cemented to prevent stored hydrocarbons from escaping to the surface, into freshwater strate, or otherwise escaping and causing waste or endangering the public helth.

(h) Monitoring and reporting.

(1) All operators of hydrocarbon scorage wells shall monitor the injection pressure and volumes of fixids or gases injected and removed for tach storage well on at least a monthly basis. Injection pressure and volumes (pjected shall be reported annually to the commission on the prescribed form. All monitoring records, including volumes withdraws, shall

be retained by the operator for at least five years. Operators storing crude

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off must also comply with other Commission rules including the filing of reports required under those rules.

[2] The operator shall report Immediately to the appropriate district office any significant lass of fluids or gases, any significant mechanical failure or any other significant problem. The operator shall confirm this report in writing within five days.

(f) lesting.

[1] Each storage well shall be tested for mechanical integrity at last once every five years. The testing shall be in a number approved by the director.

(2) The operator shall notify the appropriate district office at least five days prior to testing. Testing shall not commence before the end

of the five-day period unless authorized by the district director. (3) A complete record of all.tests shall be filed in duplicate in

the district office within 3D days after the testing. [J] <u>elugging</u>. Upon abandomment, all wells used for the injection or

removal of hydrocarbons from the facility shall be plugged in accordance with Statewide bule 14.

(k) Penalties.

(1) Violations of this rule will subject the operator to penalties and remedies specified in Title 3 of the Texas Matural Resources Code.

(2) The certificate of compliance for any underground hydrocarbon storage facility may be revoked in the manner provided in Statewide Kule 68 for violation of this rule.