Geologic and Engineering Characteristics of Gulf Region Salt Domes Applied to Underground Storage and Mining

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ABSTRACT

Salt domes have been used extensively for salt mining and underground storage of hydrocarbons. In the future, salt domes may be used also as sites for radioactive waste disposal or for compressed air energy storage. This paper provides a comprehensive review of characteristics of Gulf Region salt domes and discusses how these characteristics influence the design of mined caverns or solution cavities. Applications considered include shaft sinking, mine or storage cavity development and operations, and shaft sealing. Much of the data presented is obtained from recent investigations performed for the Strategic Petroleum Reserve and from feasibility studies for radioactive waste disposal, and has not been openly published previously.

The general structure of the dome is discussed, especially the structure at the edge of the dome, in the salt and in the adjacent sediments. Caprock features are described, in particular the structure and hydrologic properties of the salt-caprock interface. Discussion of the geology of the salt stock emphasizes anomalous features such as impurities and gas and liquid inclusions with evidence obtained from mines, drill cores, and solution mining records. Temperature gradients in Gulf region salt domes are also discussed. Finally, ranges and typical values of physical, thermal and mechanical properties of dome salt are reviewed, noting the wide range in results obtained and the sensitivity of properties such as strength and permeability to sample disturbance and testing method. Attention is also drawn to the wide variations in the secondary creep rates observed among salts from different domes.

INTRODUCTION

There are more than 500 salt domes in the Gulf regions of Texas, Louisiana and Mississippi, with approximately an equal distribution between the onshore and offshore regions. The onshore domes can be separated geographically into two major groups, the coastal and interior domes, as shown in Figure 1. The latter are further separated into three subgroups in the Texas, Louisiana and Mississippi Basins. General reviews of the geology of the Gulf region domes are given by Murray (1961) and Halbouty (1979). Statistical data regarding dome locations, depths and utilization are given by Halbouty (who also provides an extensive bibliography indexed to individual domes), Hawkins & Jirik (1966) and Jirik & Weaver (1976). All of these publications predate a large number of geological and geotechnical investigations conducted since 1977 for the Strategic Petroleum Reserve and the National Waste Terminal Storage programs (Table 1, Table 5). This paper provides a review of salt dome characteristics as obtained from these investigations as well as from the general literature. Particular attention is given to the internal characteristics of the salt stocks, and to the properties of the salt, as they affect mine or cavern design and development. No attention is given to the importance of salt domes as sources of hydrocarbons and sulphur which is well documented in the literature (e.g., Halbouty, 1979).

The major existing uses of salt domes are for salt production from conventional mines and solution caverns, and for hydrocarbon storage in solution caverns. Conventional mines are of particular importance to the present review because of the access they provide for direct examination of salt characteristics. Early mines were developed in the 19th century at Avery Island and Belle Isle but were flooded, probably because they were located too close to the surface with insufficient salt cover to prevent communication between the mine workings and overlying water-bearing sediments. The first successful mines were developed at Weeks Island and Avery Island in 1898. Subsequently, mines have been opened at Jefferson Island (1920), Grand Saline and Winnfield (1930), Hockley (1932), Belle Isle (1961) and Cote Blanche (1962). Most recently, in 1978, a new mine was opened at Weeks Island to replace the original mine, which was converted to an oil storage facility. Six conventional mines remained in production in 1982 fol-

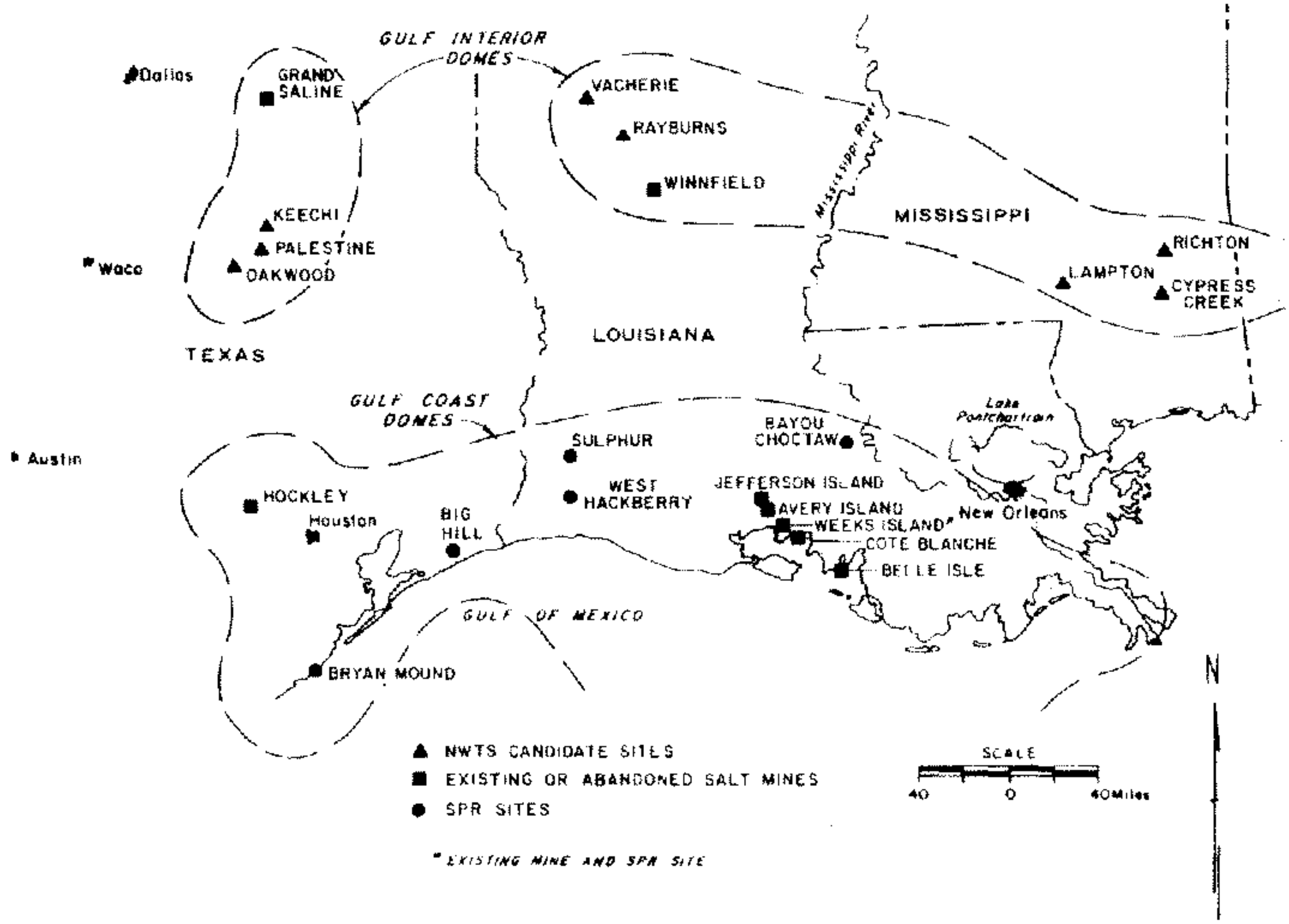


Figure 1. Locations of Domes Investigated for the SPR and NWTS Programs.

lowing flooding of the Winnfield Mine in 1965 and the Jefferson Island Mine in 1980.

Strategic Petroleum Reserve Program

Solution caverns in salt domes are used for the storage of a wide range of hydrocarbons, including crude oil, LPG and natural gas. In recent years, the most significant use of salt domes for underground storage has been by the U.S. Department of Energy for the Strategic Petroleum Reserve (SPR), which is mandated to place in storage by 1990 750 million barrels of crude oil for use in the event of an embargo of imported oil supplies. All of this storage volume is to be provided at six Gulf region salt domes: Bryan Mound and Big Hill in Texas, and West Hackberry, Weeks Island, Bayou Choctaw and Sulphur Mines in Louisiana. In all cases except Weeks Island, use is made of solution-mined caverns, including both converted, preexisting caverns and new caverns mined specifically for storage. At Weeks Island, oil is stored in a converted room and pillar mine.

National Waste Terminal Storage (NWTS) Program

The objective of the NWTS program, administered by the U.S. Department of Energy, is to construct one or more mined repositories for the disposal of nuclear wastes generated by the commercial power industry. Salt was originally proposed as a suitable host medium in 1957, since which time investigations have been conducted in bedded salt regions in Kansas, west Texas and Utah, as well as at domes in the Gulf region. Initial screening of the domes (ONWI, 1982) led to the selection of eight Gulf interior domes for detailed evaluation as possible sites: Keechi, Palestine and Oakwood in Texas; Vacherie and Rayburn's in Louisiana; and Cypress Creek, Lampton and Richton in Mississippi. Following subsequent screening, characterization studies are continuing (January, 1983) at two domes, Vacherie and Richton.

Futures Uses of Domes

It is expected that the use of domes for salt production and underground storage will continue in the future. In

TABLE 1

Bibliography of Characterization Studies Prepared for Domes in the SPR and NWTS Programs

SPR Domes	References
Bayou Choctaw	D'Appolonia (1979)
	Sandia (1980a)
Big Hill	Sandia (1981)
Bryan Mound	D'Appolonia (1980)
	Sandia (1980b)
Cote Blanche*	Golder (1977)
Sulphur Mines	Sandia (1980c)
Weeks Island	Mahtah et al (1979)
	Van Sambeek et al (1979)
	Sandia (1980d)
West Hackberry	Sandia (1980e)
NWTS Domes	**References**
Screening studies and general reports governing all domes	Anderson et al (1973)
	Ledbetter et al (1975)
	IES (1975, 1976)
	Law (1982)
	Stearns-Roger (1981)
	Simcox and Wampler (1982)
	ONWI (1982)
Oakwood	Dix & Jackson (1982)
	Kreitler & Dutton (1982)
Rayburn's	IES (1977, 1978, 1979)
	Nance & Wilcox (1979)
Richton	Drumheller et al (1982)
Vacherie	IES (1977, 1978, 1979)
	Nance et al (1979)

*Mine not selected for SPR Program.

addition to the possible use of domes for radioactive waste disposal, other suggested uses for caverns or mines in domes include disposal of hazardous chemical wastes, compressed air energy storage (Lang, 1977), and production of geothermal energy (Jacoby & Paul, 1974). In all of these cases, engineering design requires a thorough knowledge of the geology of the dome and of the physical and thermomechanical properties of the salt. This is especially so as mines or caverns are excavated at greater depths, as operating conditions become more severe (e.g., in compressed air storage), and as requirements for safety and security become more stringent. Because exploration prior to mining is practically or economically constrained, knowledge gained from other domes will be particularly valuable when applied properly.

GENERAL STRUCTURE

The general structure of salt domes is well known from a great many exploration programs. The major elements of the dome are the salt stock, the caprock and the overlying domed and adjacent upturned and faulted sediments. From the point of view of engineering developments, the major features of interest are the salt stock itself and the caprock through which shafts or boreholes must be sunk. The sediments adjacent to the dome are not of direct interest provided that the edge of the salt can be defined with reasonable accuracy.

The general structures of several domes are shown in Figure 2. These examples are chosen to illustrate variations in the size and shape of both the salt stock and the caprock. The tops of individual domes range in diameter from ½ to 4 miles with an average of about two miles. Most domes increase in diameter with depth, although mushroom-like overhangs at the top of salt and associated reductions in diameter in the depth range down to several hundred meters are also common. The depth to salt varies from a few tens to many thousands of meters. About one half of the 268 known onshore domes have depths to salt less than 1000 m and can be considered for engineering development. Salt domes extend downward to 3000 m or more, so that the bottom of the salt is not of concern in engineering applications.

The caprock may be as much as 450 m thick, but it is absent or thin, or developed only in patches on many domes. Martinez (in IES, 1975) could find no single satisfactory explanation for why some domes have thick caprocks, whereas others, often nearby, have no caprock. Possibly, the caprock thickness is related to the proportion of anhydrite in the salt or to the rate of uplift through the unsaturated ground water zone. Often the caprock has a fairly uniform thickness over the width of the dome, whereas in other cases it is thicker over the center, and in others it is present on only part of the dome (Figure 2). A thin layer of caprock may extend down the sides of the dome for several hundred or even thousands of meters, although possibly in a broken condition (Taylor, 1938). In some cases the caprock is known to overhang the salt, thus giving a misleading indication of the width of the salt stock.

At the edge of the dome, the salt (or the caprock) may abut directly against the displaced sediments, or there may be a separation occupied by a shale sheath or gouge. Kupfer (1974) supposed that the combined width of the shale sheath and an adjacent brecciated zone might be typically 300 m, varying from very thin to perhaps a few thousand meters. The nature of the edge of the dome is poorly known for Gulf region domes but has been exposed in mines in some German domes (Taylor, 1968). In most cases, the mine workings exposed a thin (1 cm to 1 m) mantle of anhydrite caprock which sharply separated the salt from the sediments. In one case, the salt and sediments were separated by 50 to 100 m of salt-mudstone breccia.

The edge of the salt at the Bayou Choctaw dome as determined from close well control is shown in Figure 3. Here, the edge is seen to be a complex melange with large blocks of salt detached from the main mass and blocks of sediment included within the salt. Although the complexity seen at Bayou Choctaw may be exceptional, it is well known from the Gulf region mines that the proportion of

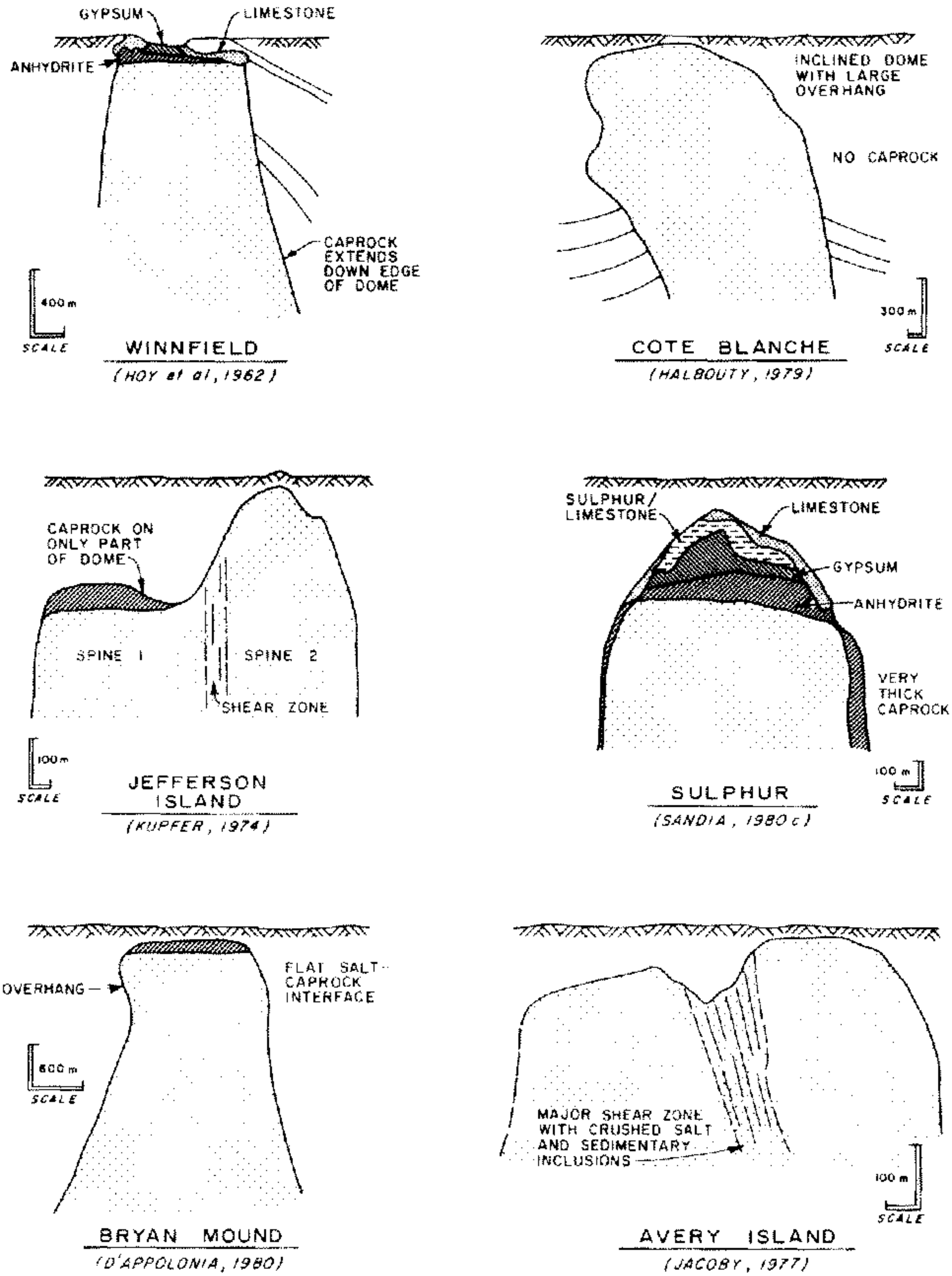


Figure 2. Typical Structures of Six Gulf Region Domes.

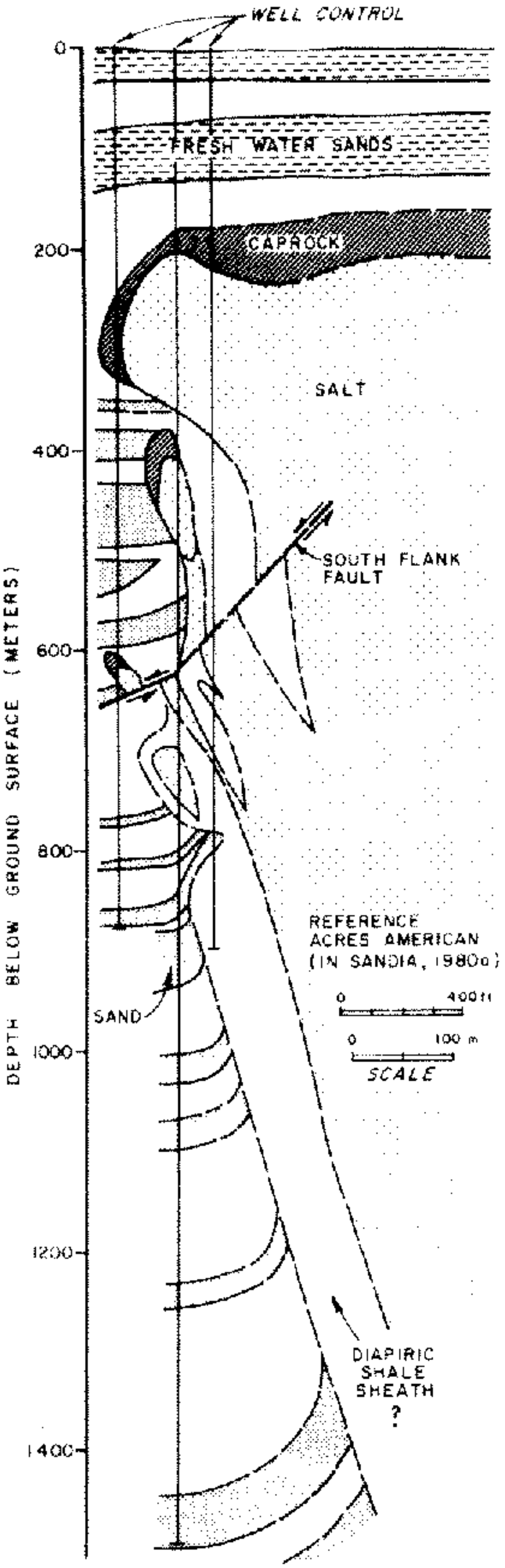


Figure 3. Inferred Geological Section of the Southwest Edge of the Bayou Choctaw Dome.

sedimentary inclusions in the salt increases toward the edge of the dome. This indicates that some degree of interslicing of the salt and adjacent sediments may be common.

CAPROCK

Lithology and Structure

Caprock lithology and, to a lesser extent, structure have been studied at many Gulf region domes. For the most part, these studies have been concerned with the origin of the caprock and have emphasized mineralogy and primary texture and structure. Comprehensive reviews are given by Goldman (1933), Taylor (1938), Walker (1974), IES (1975), and Martinez (1978). Less attention has been given to features such as secondary structure (joints and cavities) and hydrologic characteristics which are more important from an engineering viewpoint.

Typically, the caprock consists of an upper limestone zone and a lower anhydrite zone, sometimes with an intermediate mixed zone of limestone, gypsum and sulphur. These zones may be very irregularly distributed across the dome. At Winnfield, for example, the caprock has been quarried, revealing pinnacles of gypsum penetrating into the overlying limestone zone (Belchic, 1960). It is noteworthy that sulphur has been found in economic quantities only in domes located in a fairly narrow band along the Gulf Coast (Myers, 1968).

The limestone zone is often brecciated and vuggy or cavernous. Cavities may range in size from microscopic to over 300 m in length (Taylor, 1938), and in some cases may comprise up to 50% of the caprock. Cavities and fractures may be cemented with secondary calcite or they may contain sulphur, ground water, or hydrocarbons. In general, the limestone caprock zone may be manifested in boreholes or shafts by low core recovery, lost circulation and heavy water inflows possibly accompanied by hydrogen sulphide gas.

The anhydrite zone of caprock is often more massive than the limestone section, but fractures and, more rarely, cavities may be found. For example, Teas (1931) described the anhydrite in the mine shaft at Hockley as characterized by many joint systems, including horizontal and subhorizontal slicken-sided joints with pyrite coatings and other joints with dips from 45° to vertical. Extensive water-filled cavities occurred in the anhydrite caprock in the shaft at Grand Saline (Taylor, 1932). Perhaps more typically, cavities occur at the base of the caprock as described below. The basal part of the caprock may also include lenses of salt. Generally, the anhydrite rock material has a tightly interlocking fabric with an associated low porosity. Gypsum may occur, particularly at relatively shallow depths, as a replacement of primary anhydrite crystals, as void infillings or as fibrous fracture infilling.

Salt-caprock Interface

On most domes the caprock-salt interface is relatively flat, representing a solution table which truncates structural features in the salt. At both Bryan Mound (D'Appolonia, 1980) and Winnfield (IES, 1976), for example, the vertical relief of the interface over much of the dome is less than 10 feet. A flat caprock-salt interface may be regarded as typical of domes with relatively thick caprocks and is interpreted as a reflection of prolonged solution activity. In contrast, the top of the salt at Avery Island (Jacoby, 1977) is extremely irregular with sharp spines and troughs with a relief of more than 30 m (Figure 2). In this case, a deep trough is formed along a major shear zone in the salt, and subsidiary troughs have formed by preferential dissolution along parallel planes of weakness. The troughs contain loose sandy materials, probably derived from dissolution of the salt.

Two distinct types of features may be observed at the salt-caprock interface. In many cases, the bottom of the caprock consists of a layer, or pockets, of unconsolidated anhydrite sand, ranging from centimeters to meters in thickness. This sand is often found in association with extensive brine-filled cavities, and both features are taken to indicate active, or recently active, dissolution at the salt-caprock interface. Cavities or sand at the salt-caprock interface commonly result in problems during shaft sinking. In the old mine shaft at Grand Saline, for example, the caprock consisted of 6 m of cavernous limestone overlying 1.5 m of cavernous anhydrite and a 0.3-m layer of anhydrite sand at the caprock-salt interface (Taylor, 1932). During shaft sinking, 131 grout holes were required to seal this thin sand zone. Anhydrite sand and cavities were found at the salt-caprock interface in the shaft at Winnfield also. Goldman (1933) reports 7 to 10 m of anhydrite sand occurring in pockets producing brine at artesian pressures. Taylor (1938), Belchic (1960), and Hoy *et al.* (1962) describe large solution channels at the interface; grout pumped into a cavity at the interface in the Winnfield shaft was found to emerge in a surface quarry over a quarter of a mile away. Anhydrite sand and cavities have been detected by drilling on many other domes and are frequently the cause of problems with lost circulation. Further examples are given by Taylor (1938), IES (1976), Nance & Wilcox (1979), Krietler & Dutton (1982), D'Appolonia (1980) and Drumheller *et al.* (1982).

In other cases, such as in the mine shaft at Hockley (Teas, 1931) as well as Oakwood (Law, 1982) and Vacherie domes (Nance *et al.*, 1979), the salt-caprock contact is found to be sharp and tightly cemented. At several domes, some wells have encountered a tight contact, whereas other wells have penetrated anhydrite sand or cavities. This may be the general case for the majority of domes, with solution occurring preferentially in channels and troughs separated by "pillars" of solid anhydrite which support the overlying caprock.

Hydrology

There are few published data concerning quantitative hydrologic properties for dome caprock. Law (1982) reports hydraulic conductivities obtained from pump tests and straddle packer tests at two candidate domes for radioactive waste disposal. Values obtained at Cypress Creek dome were 2.1×10^{-5} cm/sec for the upper part of the caprock and 7.1×10^{-6} cm/sec for the salt-caprock interface. At Richton dome, values obtained were 7.8×10^{-4} cm/sec for the caprock and 1.8×10^{-6} for the salt-caprock interface. At Tatum dome, a pump test in the limestone zone of the caprock indicated a hydraulic conductivity of 3×10^{-3} cm/sec (USGS, 1972); this value was believed to be representative of the limestone caprock as a whole. Testing showed that the caprock aquifer was in communication with other sedimentary aquifers on the flanks of the dome and above the dome. Generally, considering all domes, it might be anticipated that hydrologic properties will be extremely variable, with highly-conductive zones likely to be found in most cases. Similarly, the chemistry of caprock water can be expected to vary both among domes and within caprock zones in a single dome. Typically, caprock ground water tends to be moderately saline and high in calcium, sulphate, bicarbonate, dissolved hydrogen sulphide and carbonaceous compounds (Walker, 1974). Conditions are probably reducing and basic or slightly acid (pH $\geq$ 6).

LITHOLOGY AND STRUCTURE OF THE SALT STOCK

Evidence regarding the internal lithology and structure of salt domes is obtained from direct observation in mines. Mapping studies have been conducted (and published) for parts of seven of the eight Gulf region salt mines (Table 2). These studies are particularly valuable in that they reveal the three-dimensional structure of the salt on a large scale, showing that the salt is often extremely heterogeneous. Considering this heterogeneity, it is noted that borehole cores and geophysical logs could present a very misleading picture of overall salt quality and structure throughout a dome. Some evidence regarding salt quality may be obtained from solution mining operations from chemical analyses of the brines and from calculations of the volumes of insolubles that accumulate in the caverns (D'Appolonia, 1979; 1980). Similarly, evidence of large-scale structural trends in the salt may be obtained from the shapes of caverns as revealed by sonar surveys. Much could be learned from systematic studies of solution caverns at various domes, but records are usually proprietary.

General Lithology and Structure

The salt in the Gulf region domes consists of halite mixed with a small proportion of anhydrite and trace amounts of other materials. Much of the salt exposed in the mines is strikingly banded with steeply-dipping bands of white, essentially pure halite alternating with thinner, darker bands which owe their color to disseminated anhydrite and internal reflection. A proportion of 5% anhy-

TABLE 2

Studies in Gulf Region Mines

Mine	Reference	Activities
Avery Island	Kupfer (1974, 1978)	Description of "Shear Zone"
Belle Isle	Kupfer (1974)	Mapping
	Kupfer (1978)	Description of Anomalous Features
Cote Blanche	Golder (1977)	Mapping Mine Stability, In Situ Permeability Tests
	Kupfer (1978)	Description of Anomalous Features
Grand Saline	Balk (1949)	Mapping
	Muehlberger (1960)	Mapping
	Clabaugh (1962)	Petrofabric Studies
	Muehlberger & Clabaugh (1968)	Review of Previous Work
Hockley	No published studies	
Jefferson Island	Balk (1953)	Mapping
	Kupfer (1974)	Description of "Shear Zone"
Weeks Island	Kupfer (1962)	Mapping
	Mahtab et al (1979)	Mapping, Mine Stability, In Situ Permeability Tests
	Van Sambeek et al (1979)	
Winnfield	Belchic (1960)	Mapping
	Hoy et al (1962)	Mapping

Additional unpublished sources are given by Kupfer (1963).

drite to salt is sufficient to impart a grey color, and salt with 15% to 25% anhydrite may appear almost black. Less commonly, the anhydrite may be found in almost continuous bands or thin slabs. In the Winnfield Mine, black slabs up to 0.5 m long and alligned parallel to the banding were found to be composed of greater than 80% anhydrite. Similar anhydrite inclusions have been found in cores obtained from other domes in northern Louisiana (e.g., Cypress Creek [Law, 1982], Richton [Drumheller *et al.*, 1982], and Vacherie [Nance *et al.*, 1979]) but are not observed in the mines in southern Louisiana.

The crystal size of the halite in the banded salt is typically in the range 5–10 mm. In hand specimens, the halite appears to be equigranular, although petrographic studies may reveal slight elongation parallel to the banding. The anhydrite occurs as laths alligned along the banding with crystal dimensions in the range 0.1 to 1.0 mm. The width of the bands is commonly in the range 25 to 250 mm, and the banding is pervasive through large areas of all of the mines. Locally, thick (>20 m) bands of massive salt are found, with no visible banding and little or no anhydrite. Commonly, the massive halite is more coarsely crystalline with giant crystals, up to 1 m in size, found in some cases. In other areas, large areas of coarsely crystalline salt may display poikiloblastic texture with all the crystals in a uniform crystallographic orientation. It is generally accepted that the coarsely crystalline salt results from dissolution and recrystallization during or subsequent to dome emplacement (Kupfer, 1963). Often, thin bands of concentrated anhydrite (apparently displaced by recrystallization of the halite) are found bordering the pure halite zones.

When exposed in three dimensions in the mines, the banding is revealed as the limbs of a complex assemblage of steeply-plunging isoclinal folds. Mapping studies show that strikes are persistent over large areas of a dome and are often subparallel either to the edge of the dome or to major structural features within the dome (see below). Average dips are generally greater than 75° and may approach 90°. Dips as low as 50° sometimes occur and may be more frequent in the interior domes (Kupfer, 1963). Toward the edge of a dome, dips may be expected to be parallel to the dip of the outer edge of the salt, and dips toward the center of the dome may be indicative of a salt overhang (Kupfer, 1968; Hoy *et al.*, 1962).

Shear Zones

Many domes contain small proportions of shale and sandstone derived either from material which was originally deposited with the salt or from material that was incorporated into the dome during its upward displacement. Close to the edge of a dome, sedimentary material might be incorporated by shearing as slices of shale sheath are caught between slices of salt and then further broken up during subsequent upward movement (Kupfer, 1974). Within a dome the sedimentary material might be shale sheath which is caught between adjacent spines of salt which were intruded independently (Balk, 1949, Kupfer, 1974).

Kupfer referred to the sheared zone at the edge of a dome as an "external shear zone" which might be identified by shearing within the salt (i.e., banding with constant strike parallel to the edge of the dome with little evidence of folding) as well as by high proportions of impurities. In the Weeks Island Mine, Kupfer found evidence of distinctive shearing extending 150 m into the dome from the edge of the salt. In the Belle Isle dome, a hole drilled 100 m from the edge of the salt encountered 40% to 50% shale mixed with salt (Kupfer, 1974). It is common practice in the Gulf region mines to avoid mining within 100 m of the edge of the dome. This is evidently sound practice, but it excludes direct observation of the nature of the salt close to the edge of the dome.

Shear zones within the salt mass were designated by Kupfer as "boundary shear zones" in cases where sedimentary material was found, and "internal shear zones" in cases where there was evidence of pronounced shearing but no sedimentary material. Boundary shear zones have been observed by Kupfer (1974, 1978) in the Avery Island, Belle Isle, Jefferson Island and Weeks Island mines where they are commonly associated with anomalous features such as brine and oil seeps and gas pockets (see below). Boundary shear zones may be from 3 m to greater than 100 m wide, and they may be very extensive in both the lateral and vertical directions. A striking example is the major shear zone in the Avery Island dome which has been eroded to form a marked depression in the top of the salt (Figure 2). In contrast, there may be many domes which do not contain a major shear zone.

Impurities

Anhydrite is the major impurity in the Gulf region salt occurring in disseminated form in all domes and in thin slabs in some domes. Because the anhydrite is heterogeneously distributed, it is very difficult to estimate the average anhydrite content throughout a particular dome or even in a part of a dome, especially from limited borehole data.

To summarize the available data, the normal banded salt in some domes may contain less than 2% anhydrite with only trace quantities of other insoluble material (Table 3). In other domes such as Bryan Mound (D'Appolonia, 1980) the proportion of anhydrite in the normal salt may be as high as 4% to 5%. In all domes the proportion of anhydrite will vary by a few percent across the banding, and there are likely to be zones (perhaps large) in which the anhydrite content is 10% or greater. Similar conclusions were previously drawn by Taylor (1938). No clear geographic trends exist as to which domes are likely to be more or less pure, although it has been suggested that the inland domes tend to be less pure (especially in Louisiana). A clearer distinction is that the inland domes are more likely to contain continuous, thin beds or slabs of anhydrite, whereas the anhydrite in the coastal domes may be entirely disseminated. Generally, a major factor affecting purity is the presence of shear zones within the salt stock.

Dome salt also includes small amounts of sedimentary material and potassium or magnesium-bearing minerals. These materials may be concentrated along linear trends (especially shear zones) and locally may affect mining or solution cavern development. A few domes might contain

TABLE 3

Anhydrite in Gulf Region Salt Determined by Laboratory Testing

Dome	Number of Samples	% Insolubles Range	% Insolubles Mean	$\%CaSO_4$ Range	$\%CaSO_4$ Mean	Reference	Comments
Avery Island	112	0.02–0.27	0.09			Jacoby (1977)	Samples taken at 10' intervals from continuous channel, not representative of overall dome
	5	2.7–7.0	4.3			Taylor (1938)	From various parts of dome
Cote Blanche	100	0.3–1.1	0.7	0.3–1.2	0.8	Golder (1977)	Samples from 1' intervals in exploratory boreholes—ranges refer to composite averages for core boxes
	362	0.7–4.7	2.2	2.0–5.4	2.9		
	863	0.3–0.9	0.7	0.7–1.2	1.0		
	813	0.6–1.2	0.9	0.9–1.3	1.1		
	445	1.4–4.7	2.4	1.6–2.2	1.7		
Grand Saline	2		1.1			Balk (1949)	"Pure" mine with few inclusions
Tatum	20	1.2–22.0	9.1			WES (1963)	Samples from exploratory borehole
Richton	25	0.03–19.2	2.0			Drumheller et al (1982)	Samples taken at 20' intervals in exploratory borehole
Vacherie	130	0–32.9	1.6			IES (1979)	Samples taken at 20' intervals in exploratory borehole
Rayburn's	128	0–27.2	2.3			IES (1979)	Samples taken at 20' intervals in exploratory borehole
West Hackberry	3	1.9–3.9	2.8	2.8–5.1	3.8	Sandia (1980e)	Samples represent range of quality from "most transparent" to "darkest" in 14 m core from 2 holes
	"Composite"				4.0	Taylor (1938)	Mean of unknown number of core samples
Bayou Choctaw	"Composite"				2.1	Taylor (1938)	Mean of unknown number of core samples
Bryan Mound	455			2.2–33.1	7.2	D'Appolonia (1980)	Samples taken at 5' intervals
							Dow Well #4 (may be % insoluble)
	382	0.03–18.2	4.8				Samples from Dow Well #1
	8	1.3–4.9	3.3	1.9–6.1	4.6	Sandia (1980b)	Samples from 5 different wells
Jefferson	5	1.0–2.3	1.7			Taylor (1938)	Samples from various parts of mine
Island	6	1.0–20.0	12.5			Taylor (1938)	Samples from oil well (may be close to edge of dome)

Taylor (1938) gives values for % insoluble residue for random samples for 19 domes:
range (excluding slab anhydrite) = 0.2–29.3%
mean (76 samples, composite for all domes) = 5.5%

larger proportions of potassium minerals. For example, sufficient sylvite was found in the Palangana dome for potash mining to be considered (Hofrichter, 1968).

ANOMALOUS FEATURES

A number of "anomalous features" (Kupfer, 1978) which occur in some salt domes have been described earlier in the paper. These include sedimentary inclusions, sylvite anomalies, sheared salt, coarse recrystallized salt and dark salt with a high anhydrite content. Other anomalous features found in domes include small oil seeps and, with particular significance to mine development, brine seeps and gas pockets. Kupfer has noted that these features often occur in association and that they may be diagnostic of external (edge of dome) or boundary shear zones.

Brine Seeps

Brine seeps occur in several of the Gulf region mines and have been studied over a period of several years by Louisiana State University (IES, 1976, 1977, 1978, 1979; Kumar & Martinez, 1981). The Grand Saline, Hockley and Cote Blanche Mines are reportedly essentially dry, whereas seeps have occurred in the Avery Island, Belle Isle, Weeks Island, Winnfield and Jefferson Island Mines. In most cases, the amount of seepage is a maximum when first exposed, and it declines with time and stops after a few months. In a few cases, seepages or "leaks" occurring close to the edge of the dome have been known to increase with time and have required remedial action. The brines are generally NaCl, but $CaCl_2$ has also been recorded.

The Winnfield Mine was flooded in 1965 via a leak that was discovered in an abandoned area of the mine as a 4-inch jet of water. The mine was flooded within two days of discovery of the leak. IES (1976) suggested that the water was probably derived from cavernous zones at the caprock-salt interface or in the caprock. This water then percolated through 125 m of salt to create the leak into the mine. The mechanism by which fractures could be created extending this far below the top of the salt is not known. Prior to the flooding, the mine experienced only minor brine seeps, which declined with time (Hoy *et al.*, 1962).

The Jefferson Island Mine was flooded in November, 1980, by waters draining from an overlying lake (MSHA, 1981). This occurred immediately after a drilling rig operating in the lake had lost circulation, but the exact cause of the catastrophe is unknown. Prior to the flooding, several major leaks had been encountered in the mine (IES, 1979). Two leaks were associated with an old exploration borehole, and a third occurred when the mine penetrated to within 30 m of the edge of the dome. The latter seepage was proven by chemical and isotopic analyses to be meteoric water (IES, 1979; Knauth *et al.*, 1980). A fourth leak occurred when an exploratory borehole on the 400-m level encountered a pocket which drained 200 m^3 of $CaCl_2$ brine.

Prior to the purchase by DOE in 1977, the Weeks Island Mine had a history of minor brine seeps, all of which tended to stop with time, indicating drainage from isolated brine pockets in the salt. The separation between the mine and the upper surface of the salt had been maintained at greater than 100 m (Sandia, 1980d). Following the purchase, the original mine operators developed a new mine adjacent to the old mine and at a slightly higher elevation within the dome. One of the drifts to this new mine developed leaks to the extent that the drift was abandoned and sealed off with a bulkhead. Substantial grouting from surface and underground has significantly reduced but not completely eliminated the leak. Drilling and dye injection from the surface have proven that the water entering the drift originates from the overburden above a dome at a point where the salt thickness is approximately 90 m.

The Avery Island Mine has a long history of minor leaks at many points in the mine, all of which have been successfully controlled, though not eliminated, by grouting (Jacoby, 1977). The Avery Island dome contains a major fault zone which includes a high proportion of sandstone, as shown in Figure 2. The upper surface of the salt is highly irregular, with a deep trough along the fault zone and sediment-filled crevices developed along banding parallel to the fault. Leakage into the mine appears to be associated with these crevices and related fractures that must extend at least 150 m below the top of the salt. (Cavities in the salt close to the top of the dome were also found in an exploratory well at the Bayou Choctaw dome [Sandia, 1980a]. A 4-m void was found 30 m below the top of salt and a 0.6-m void was found 44 m below the top.)

Kumar & Martinez (1981) and Knauth *et al.*, (1980) have respectively examined the major element and isotopic chemistry of brines collected from leaks in the Weeks Island, Belle Isle and Jefferson Island Mines. In only two cases, at Weeks Island and Jefferson Island described above, the brine was found to be meteoric in origin. In all other cases the water originates from formational waters (not connate evaporite water) which became trapped in the salt during intrusion.

Gas Inclusions and Pressure Pockets

Gas occurs to some degree in the majority (if not all) of the Gulf region mines and is frequently encountered in holes drilled into the salt in other domes. Frequently the gas is rich in methane; gas recovered from a well at Bryan Mound, for example, contained 92% CH_4 with 5% CO_2 and traces of nitrogen, ethane and propane (D'Appolonia, 1980). In other cases, the gas is richer in carbon dioxide; at Winnfield a sample contained 47% CO_2 with 17% H_2O, 18% N_2, and small amounts of CO, O_2, SO_2, H_2, CH_4, A and C_2H_2 (Hoy *et al.*, 1962). Gas encountered at Avery Island contains H_2S and N_2 but no CO_2 (Jacoby, 1977). Gas from the Lake Hermitage dome was found to be 97% N_2 with 3% CO_2 (Taylor, 1938). Often the gas occurs only in small amounts and is barely noticeable during drilling or mining. In some domes gas occurs in large quantities and is a hazard to mining unless proper precautions are taken. Methane emissions monitored from a drift advanced through a zone of dirty salt in the Belle Isle Mine ranged from 1 to 3 m^3/ton of salt mined (Iannacchionne *et al.*, 1982). Belle Isle appears to be an example of a dome which is significantly more gassy than the other domes with developed mines.

Gas probably occurs throughout the salt in small quantities in many domes in intragranular bubbles and intergranular cracks. Concentrations ("pressure pockets") occur locally as sometimes manifested by the gas "outbursts" or "blowouts" observed in several mines. As described by Kupfer (1978), these outbursts are rounded, conical or vertically-elongated, pipe-line or chimney-like openings which develop during blasting, generally in the roof but also in the wall inclined upwards. Some examples are cornucopia-shaped and twist upward into the roof (in extreme cases) for more than 60 m. These larger examples have a diameter in the mine roof of greater than 15 m. Typically, the walls of the outburst display a characteristic fracture pattern that has the appearance of overlapping shingles. When the outbursts form, up to tens of thousands of tons of granulated salt and large volumes of gas are emitted. There are no confirmed reports of outbursts in the floor other than a report of a floor heave at Winnfield by Belchic (1960).

Outbursts have occurred in the Jefferson Island, Weeks Island, Cote Blanche, Belle Isle and Winnfield Mines (Kupfer, 1978). Both the vertical extent and diameter of the outburst cavity appear to increase with depth, although there are obvious exceptions (Table 4). The largest examples (about 75 m high) are found at Jefferson Island and Belle Isle. In one case at Belle Isle, an outburst expelled about 10,000 m^3 of salt and a large volume of gas and resulted in a major explosion and loss of life (MSHA, 1979). No outbursts have been encountered at Avery Island, even though gas is found in the salt. This may be because the mine levels are relatively shallow and because the gas is released through the extensive series of fractures present near the top of the salt.

Possible mechanisms for outbursts have been discussed by Thoms & Martinez (1978) and Mahtab (1982). Clearly, the outbursts occur as a result of a violent release of trapped gas pressure. With one possible exception (at Winnfield, reported by Thoms & Martinez, 1978), all of the outbursts in the Gulf region mines have occurred during blasting (i.e., during active mining). Similar features observed in German mines have been triggered by mechanical or solution mining (Gimm & Pforr, 1964). It is thus concluded that outbursts occur when mining encroaches sufficiently close to a zone of high pressure gas that the pressure is sufficient to burst through the remaining web of rock. Mahtab ascribes the shingle-like jointing to brittle failure in a biaxial stress field, a process akin to core discing. The absence of outbursts in the floor may be attributed to stress relief by undercutting prior to blasting (Thoms & Martinez) or to the confining effect of the salt released from the upward outburst (Mahtab).

The nature of the gas pockets is not well known, although it seems more likely that the gas is contained in cracks and

TABLE 4

Gas Outbursts in Gulf Region Mines

Mine	Approximate Depth to Mine Floor (m)	Number of Reported Outbursts	Maximum Observed Height (m)	Reference
Grand Saline	213	None		
Avery Island	150	None		
	230			
	275			
Weeks Island	90	None		Mahtab et al (1979)
	180	None		MSHA (1978)
	240	12	18	
Winnfield	250	6	~60	Hoy et al (1962) Thoms & Martinez (1978)
Cote Blanche	400	15	18	Golder (1977) Kupfer (1978)
Jefferson Island	245	None		MSHA (1978)
	300	None		
	410	3	85	
	470	None		
Belle Isle	425	10	~90	MSHA (1979)
Hockley	475	None		

connected pores than in large caverns. Thoms & Martinez imagined the gas concentrated in vertical, cylindrical zones which were elongated by the upward movement of the salt. Mapping in the mines shows that the outbursts are often aligned along structural trends. At Winnfield (Hoy *et al.*, 1962), and possibly at Belle Isle (Kupfer, 1978), the outbursts occur close to the edge of the dome. In other cases (e.g., Cote Blanche and Belle Isle) the outbursts follow structural trends such as shear zones within the dome (Kupfer, 1978). In all cases, there is an association between gas occurrence and other anomalous features such as dirty salt, sediment inclusions and oil or brine seeps. Sediment inclusions may be the features most likely to be diagnostic of trapped gases.

SALT DOME TEMPERATURES

Reliable temperature data from the interiors of domes are seldom obtained. Temperatures recorded in mines may be unreliable unless they are rock temperatures measured away from the influence of the rooms. Similarly, well logs are unreliable unless the fluids in the well have been allowed to equilibrate over a period of several months. Also, temperatures from wells in the sediments adjacent to a dome will not accurately reflect temperatures within the salt. Selig & Wallick (1966) demonstrated by analytical modeling that at depths less than about 200 m temperatures within the dome will be higher than those at corresponding depths outside the dome. Similarly, temperatures in the center of a dome will be higher than temperatures at corresponding depths closer to the edge of the salt. These differences arise because salt has a thermal conductivity typically five times higher than that of clastic sediments. Geothermal gradients may be expected to be lower in the salt than in the adjacent sediments but higher in the sediments overlying the salt.

The available data for internal salt dome temperatures obtained from measured rock temperatures in four mines and from equilibrated well logs from five other domes are shown in Figure 4. The data from the mines form a narrow linear trend but indicate lower temperatures at corresponding depths than those found in the other domes. Probably these differences reflect variations in the regional geothermal gradient which is about 2.2°C/100 m in the vicinity of the Five Islands mines, but as high as 3.8°C/100 m near the Vacherie dome (Moses, 1961). At comparable depths in different domes temperatures may vary by 20°C or more. Temperatures within domes cannot be estimated accurately from the regional geothermal gradient.

ENGINEERING PROPERTIES OF DOME SALT

Investigation of the engineering properties of dome salt has been extensive in recent years due to the interest in underground storage in the Gulf Coast region. Reviews of the properties of bedded and dome salt have been given by Isherwood (1981), Gevantman (1981), and Dames and Moore (1978), but these do not account for the extensive testing conducted recently for the NWTS and SPR programs. Although many of the properties of dome salt are well characterized, others are poorly understood even though extensive testing may have been performed. Previous portions of this paper emphasized the heterogeneity of dome salt from a geologic point of view. Similar heterogeneity is found in the engineering properties of salt, but there has been little success in correlating variation in engineering properties with factors such as mineralogy or fabric. In compiling salt properties, it is necessary to note that many properties vary according to the test procedure that is used.

Typical values and ranges of values for selected engineering properties of dome salt obtained from 15 Gulf region domes are listed in Table 5. While limited space does not permit tabulation of properties for each dome, Table 6 lists references which give properties for specific domes.

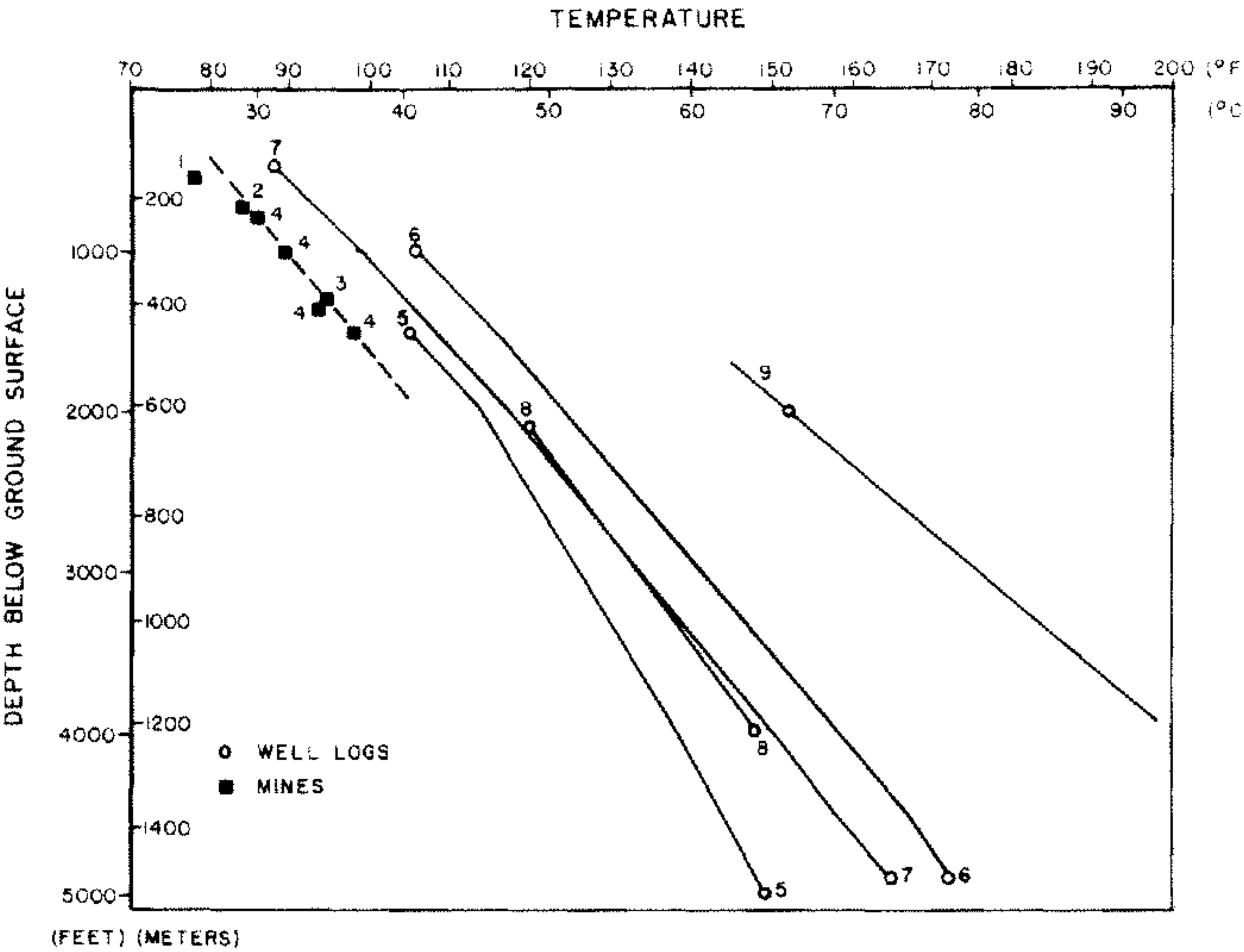
Physical Properties

Bulk density is one of the few properties of salt which typically falls in a rather narrow range from 2.10 to 2.23 g/cm^3, depending on porosity and the degree of impurities. A typical value is 2.16 g/cm^3. Porosity is generally of little interest by itself, but it has some influence on strength and permeability, as discussed below. Although few direct measurements of porosity have been made on dome salt, a representative value is on the order of one percent with a range from 0.2% to 6%.

Measurements of water content in salt indicate very low values, generally less than 1% and frequently less than 0.1%. These measured differences result from variability in the salt as well as from different sampling and measurement techniques. Roedder and Bassett (1981) note that most published values of water content are not comparable due to differing measurement techniques, and that many measurements contain serious errors which tend to underestimate water content. The total water content in salt is composed of three portions: hydrous minerals, intergranular pore fluids and intragranular water. Different measurement techniques measure different portions of this total water content. Even though the total water contents in dome salt are very low, they may be very important with respect to the storage of nuclear wastes in salt because of the potential for thermally-induced brine migration and resultant effects on corrosion of waste packages (e.g., Olander *et al.*, 1980).

Permeability

The measured permeability of dome salt is highly variable and is extremely sensitive to measurement method. The values determined in situ generally fall in the range of 0.0001 md to .01 md. Laboratory values have a similar lower limit but can range up to several hundred md. Differences between laboratory and *in situ* permeability val-



DOME	REFERENCE
1. AVERY ISLAND MINE	VAN SAMBEEK (1981)
2. WEEKS ISLAND MINE	AUTHOR'S FILES
3. COTE BLANCHE MINE	GOLDER (1977)
4. JEFFERSON ISLAND MINE	PERSONAL COMMUNICATION
5. EMINENCE WELL LOG	PERSONAL COMMUNICATION
6. VACHERIE WELL LOG	PERSONAL COMMUNICATION (R. THOMS)
7. RAYBURN'S WELL LOG	PERSONAL COMMUNICATION (R. THOMS)
8. BRYAN MOUND WELL LOG	D'APPOLONIA (1980)
9. BAYOU CHOCTAW COMPOSITE LOGS	SANDIA (1980A)

ALL DATA ARE FROM WITHIN THE SALT STOCK

Figure 4. Salt Dome Temperatures.

ues can be attributed to sample disturbance and the effects of confinement. The processes of extracting, transporting and testing a sample cause loosening, which tends to increase the permeability. Laboratory-measured permeabilities can vary by several orders of magnitude, depending on confining stress as shown in Figure 5. Variations in measured permeability under confined conditions can be attributed to variations in porosity (Figure 6).

Mechanical Properties

Because of the plastic nature of salt, the conventional mechanical properties of strength and deformability are

TABLE 5

Representative Values of Engineering Properties of Gulf Region Dome Salt

Property (Units)	Range of Measured Values	Typical Value	Remarks
Bulk Density (g/cm^3)	2.10–2.23	2.16	Depends on porosity and degree of impurities
Porosity (%)	0.2–6.0	< 1.0	Not often measured directly
Water Content (%)	0.001–1.7	< 0.1	Sensitive to measurement technique, few comparable measurements on different salts
Permeability (md)			
—Laboratory	0.0001–400	—	Significantly affected by sample disturbance, sensitive to confining stress
—Field	0.0001–0.011	0.001	
Tensile Strength (MPa)	0.2–3.5	1.0	Indirect measurement (Brazilian test), at room temperature
Unconfined Compressive Strength (MPa)	8–29	23	At room temperature
Young's Modulus (GPa)	21–42	30	Values from unload/reload cycles in quasi-static tests at room temperature
Poisson's Ratio	0.15–0.5	0.35	Values from unload/reload cycles in quasi-static tests at room temperature
Creep Properties	—	—	See text, Table 6, Figures 9, 10
Thermal Conductivity (W/mK)	2.0–6.5	5	Decreases with increasing temperature. Typical value corresponds to room temperature.
Thermal Diffusivity (m^2/s)	$1.3–3.7 \times 10^{-6}$	3×10^{-6}	Decreases with increasing temperature, typical value corresponds to room temperature
Coefficient of Linear Thermal Expansion (K^{-1})	$4.7–5.7 \times 10^{-5}$	5×10^{-5}	Increases slightly with increasing temperature, very few measurements available

Note: Values based on tests reported in literature as indicated in Table 6.

complex and difficult to define and are highly sensitive to test procedure. Behavior is often non-linear and inelastic, so that the measurement and application of mechanical properties must carefully consider the load path (i.e., loading or unloading), magnitude of stresses and time scale of loading relevant in the field. Elastic properties characterize salt behavior only for relatively low deviator stresses, low temperatures, and short time periods. The inelastic properties (creep, plasticity) are applicable to all conditions but are increasingly important under higher stresses, higher temperatures and longer time periods. Thus, although the conventional parameters of tensile strength, unconfined compressive strength, triaxial compressive strength and Young's modulus (all under specified temperatures and short duration [quasi-static] conditions) can be used as indices of mechanical behavior, engineering design requires careful consideration of the problem of interest with respect to the stress and temperature levels and the rate of deformation.

Hansen *et al*. (1982) provide a comparison of strength measurements on salt from six Gulf region domes (and also four bedded salt sites). This comparison is particularly valuable because it is made on the basis of common test procedures (all performed by one organization), and because an attempt was made to correlate strength with petrology. While Hansen *et al*., observed that strength varies considerably among the sites, no correlation between strength and specific petrological characteristics could be established.

The tensile strength of dome salt ranges from 0.2 MPa to more than 3 MPa, with 1.0 MPa being a typical value. The unconfined compressive strength shows a narrower range of variation, with 23 MPa being a typical value. It may be noted that in salt, the ratio of compressive strength to tensile strength is typically more than 20 whereas a value of 10 is typical for brittle rocks. The unconfined compressive strength appears to be related to porosity, as illustrated in Figure 7, and high porosity may be the cause for some salts (e.g., Weeks Island) to be noticeably friable *in situ*. Alternatively, the friability may be the result of a different crystal fabric occurring in recrystallized salt. The strength of salt in triaxial compression is difficult to define because of the increasingly plastic behavior with confinement. As demonstrated by Hansen *et al*. (1982), conventional failure criteria (e.g., Mohr-Coulomb, parabolic fit) generally do not fit well to the highly non-linear strength envelopes typical for salt.

The "elastic" deformability properties of Young's mod-

TABLE 6

Sources of Information for Engineering Properties of Dome Salt

	Physical				Mechanical				Thermal		
Dome	Density	Porosity	Water Content	Permeability	Tensile Strength	Compressive Strength	Deformability	Creep	Conductivity	Diffusivity	Coefficient of Linear Expansion
Avery Island	16	6	6,13		6,10	6,10	6,10	7,8,9,11, 27	3,16	3,12	3
Bayou Choctaw	17		17		17	17,29	17,29				
Belle Isle			13								
Bryan Mound	25					25,29	25,29	25			
Cote Blanche	4			4	4,10	4,10	4	14			
Grand Saline		1		1,28				14,21			
Hockley								14,21			
Jefferson Island	16,19		13,19	22	10,19	10,19	10,19	5,6,11,19	16		
Rayburn's			13								
Richton					10,18	10,18	10,18	18			
Tatum	26	26	26	26	26	26	26	26,2			
Vacherie			13		10,18	10,18	18,10	18			
Weeks Island		1	13	1,15,23	10,23	10,23	10,23				
Winnfield		1		1							
West Hackberry						20,24,29	24,29	24			

1. Aufricht and Howard (1961)
2. Chabannes (1982)
3. Durham and Abey (1961)
4. Golder (1977)
5. Hansen (1977)
6. Hansen and Mellegard (1980a)
7. Hansen and Mellegard (1980b)
8. Hansen and Carter (1980)
9. Hansen and Carter (1982)
10. Hansen et al (1982)
11. Herrmann and Lauson (1981)
12. Smith (1976)
13. Knauth and Kemar (1981)
14. Lomenick and Bradshaw (1969)
15. Mahtab et al (1979)
16. Morgan (1979)
17. PB/KBB (1978)
18. Pfiefle et al (1981)
19. RE/SPEC (1977)
20. Tillerson (1979)
21. Thompson and Ripperger (1964)
22. Thoms and Gehle (1982)
23. Van Sambeek et al (1979)
24. Wawersik et al (1980a)
25. Wawersik et al (1980b)
26. WES (1963)
27. Mellegard and Senseny (1981)
28. Reynolds and Gloyna (1960)
29. Price et al (1981)

ulus and Poisson's ratio are very sensitive in salt to load paths, confining pressure, temperature and time. Reported values thus require careful interpretation. For example, the initial loading modulus is usually much lower than the unloading/reloading modulus. Although the unloading/reloading modulus is generally more applicable to elastic analyses of salt, many reported tests on salt are based on initial loading values. The values for Young's modulus and Poisson's ratio in Table 5 are based on unload/reload tests. Typical values are 30 GPa and 0.35, respectively. As noted by Hansen *et al.*, (1982), variation in elastic properties for salt is not as great as the variation of strength properties, provided common test procedures and interpretations are used.

Creep Properties

The greatest complexity and variability in salt behavior is observed in the time-dependent deformation (creep) properties. Often, these properties have the greatest significance for engineering design purposes. Although the exact mechanisms and quantitative descriptions of creep are a subject of considerable debate, it is generally recognized that creep occurs in three different phases (Figure 8). Primary (transient) creep refers to the initial stage of loading (under constant stress and temperature) when deformation rate is decreasing with time. Secondary, steady-state, creep refers to a deformation rate that is constant with time. Tertiary creep sometimes follows secondary creep and exhibits an increasing rate of deformation with eventual rupture. Tertiary creep is apparently regarded as having minor practical significance, and has received little attention by researchers. Primary and secondary creep are important in nearly all engineering applications. While a thorough discussion of creep behavior is beyond the scope of this paper, certain key aspects relevant to engineering applications will be pointed out.

Hansen and Carter (1982) provide a valuable discussion of various analytical expressions used to describe the creep behavior of salt. Many different expressions have been used in the past by various researchers, frequently indicating very different types and magnitudes of creep strain. It appears that a creep equation of the following form is gaining acceptance as a reasonably accurate expression to describe both primary and secondary creep:

$$e = e_t[1 - \exp(-rt)] + \dot{e}_s t \qquad (1)$$

where e is total creep strain, e_t and r are experimental fitting parameters, t is time, and $\dot{e}_s$ is the secondary creep rate. The first term, which predicts a decrease in creep rate with time, represents primary creep. The second

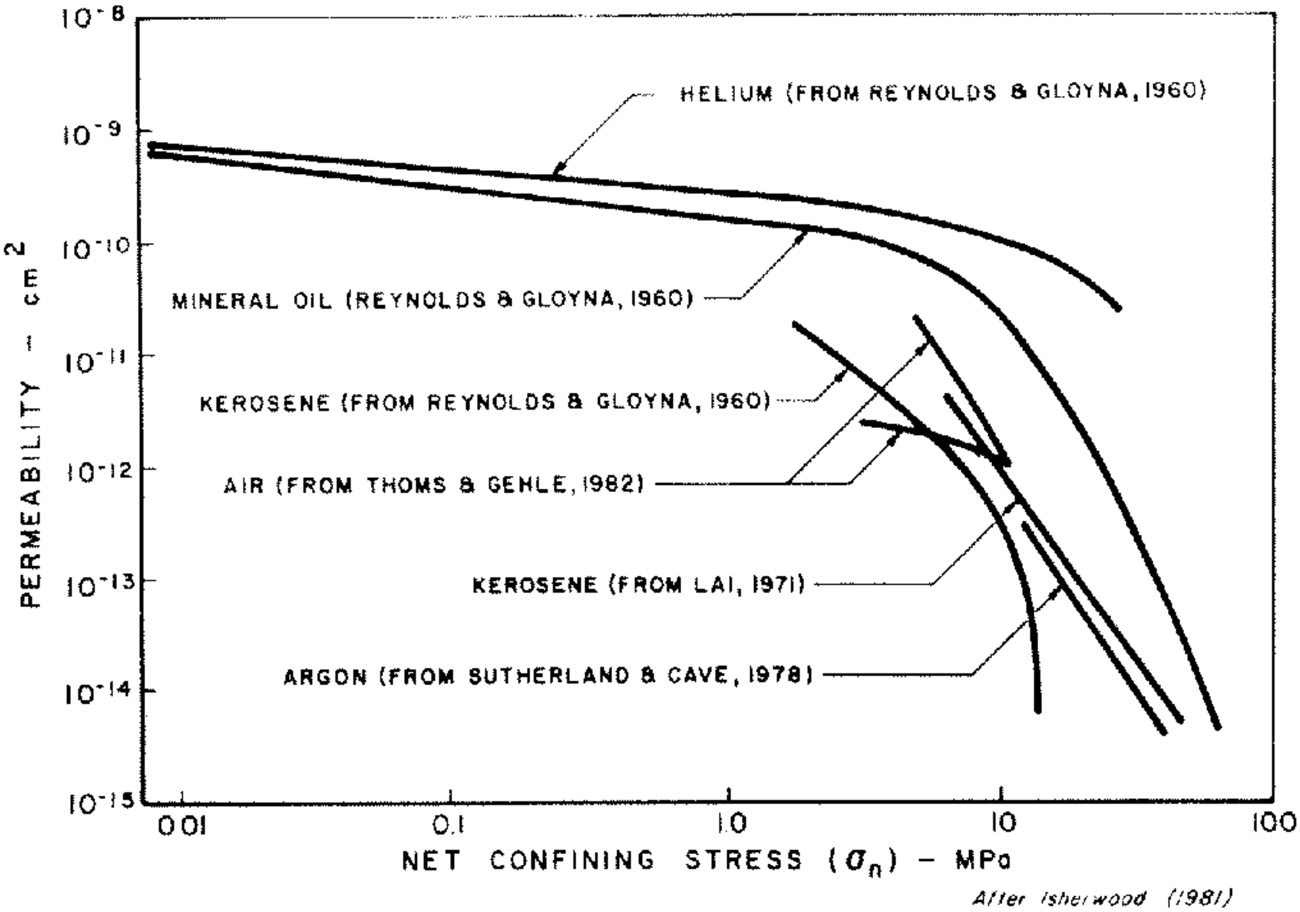


Figure 5. Permeability of Salt as a Function of Hydrostatic Confining Pressure.

term, which predicts a constant creep rate (under constant stress and temperature) represents secondary creep. The secondary creep rate is described by:

$$\dot{\varepsilon}_s = A\,\sigma^n \exp\left[-Q/RT\right] \qquad (2)$$

where A, n and Q are experimental fitting parameters, σ is a measure of shear stress, T is the absolute temperature, and R is the universal gas constant.

Fitting parameters for the above equations have been determined for a number of dome salts. Secondary creep rates for salt from six domes at different stress levels, based on curve fitting of laboratory data using Equation (2) are presented in Figure 9. Under equal conditions of stress and temperature, the variation in the rate of strain among different sites is up to two orders of magnitude. It is interesting to note, however, that for any given site the degree of scatter in the data used to develop the constants in the secondary creep equation may be very large. Figure 10 shows specific data points from tests performed on various dome salts, superimposed on the range of variation exhibited by bedded salt from the WIPP site in southeastern New Mexico which has been tested very extensively. It appears that although the average creep rates vary greatly among sites, collectively the data lie roughly within the same very wide band. This raises the question of whether all sites exhibit a large variation in creep rate, which would be revealed only by additional testing. The reasons for the variation in creep rate among sites and within a single site are not apparent. Probably the variation does reflect inherent differences among the samples (although variation in test technique may have some influence), but no correlation has been established with factors such as fabric or the nature or degree of impurities.

The large variability in the creep data and the laws which are derived from the data is particularly significant when creep must be extrapolated over long time periods. Creep tests which have been run for only days or weeks are sometimes used to predict rates of deformation over periods of tens to hundreds of years. There is clearly a need to run creep tests for much longer durations than have currently been performed in order to validate long-term predictions. Furthermore, it is important to determine whether the variability observed in the laboratory is reflected by in situ behavior. To date, there have been few comparisons between predicted closures of underground openings based on laboratory testing and analysis and ac-

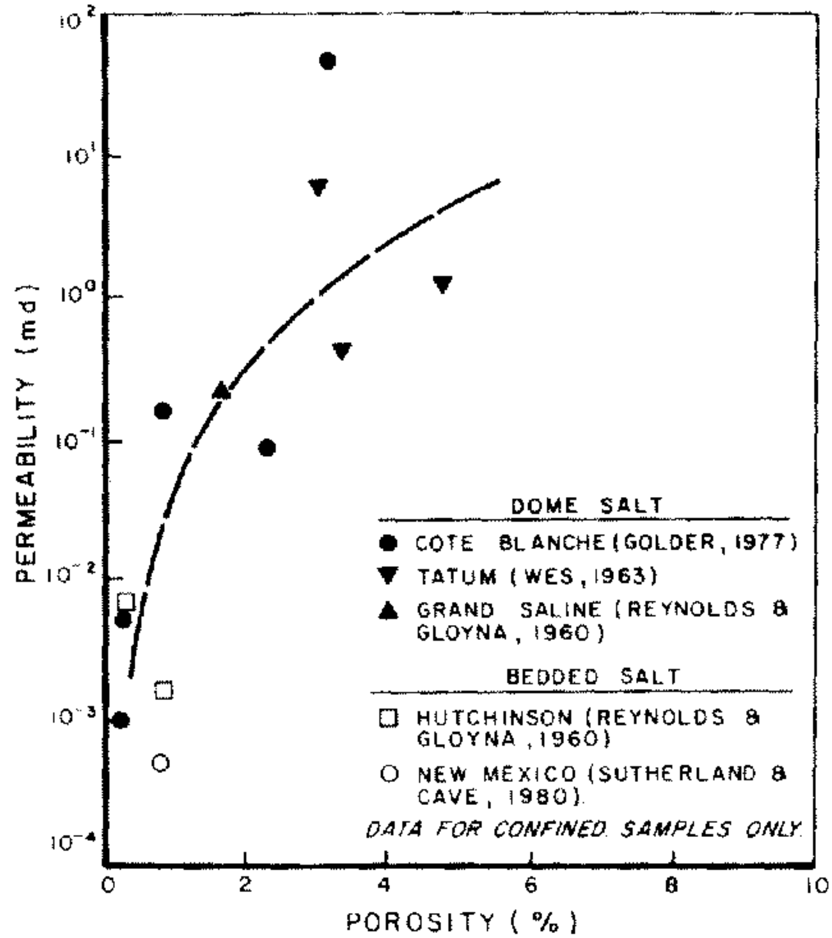


Figure 6. Permeability of Confined Dome and Bedded Salt as a Function of Porosity.

tual measurements. Preece and Stone (1982) obtained good agreement between modeling results and actual performance of storage caverns in the Bayou Choctaw and Eminence domes, even though material properties used in the analysis were obtained from a different site (West Hackberry). The agreement is remarkable, considering the large variation in creep parameters from various sites discussed above. Further, such comparisons would be extremely useful as a means for validating laboratory creep tests as tools to predict *in situ* behavior.

Thermal Properties

The thermal properties of salt are particularly important to nuclear waste storage, where large amounts of heat must be dissipated through the rock. A limited number of measurements of thermal conductivity of rock salt exhibit a large variation, which is probably related to factors such as grain size, microfracturing, degree of impurities and moisture content. Thermal conductivity is observed to decrease significantly with increasing temperature from 3 to 6 W/mK at room temperature to values from 2 to 4 W/mK at temperatures of 200 to 300°C. These values are generally lower than conductivity values measured in single crystals or on artificially prepared samples of salt, presumably because of flaws or impurities in the natural samples. Typical values for thermal diffusivity and the coefficient of thermal expansion of dome salt, obtained from limited testing, are given in Table 5.

Discussion

Laboratory testing of salt often reveals a very wide scatter in test results. Sample disturbance (due to stress relief) may be a major factor contributing to this scatter, particularly in the case of tests (e.g., permeability) conducted under conditions of zero or low confining stress. Another factor contributing to the scatter may be inherent differences in mineralogy or fabric, although direct correlations among properties are difficult to establish. A study of the effect of anhydrite content on the strength of synthetic rock salt (Price, 1982) indicated that anhydrite contents of less than 25% have little effect on salt strength. This might support the supposition that properties such as strength and creep may be strongly affected by quite subtle variables in fabric, which cannot be detected by routine

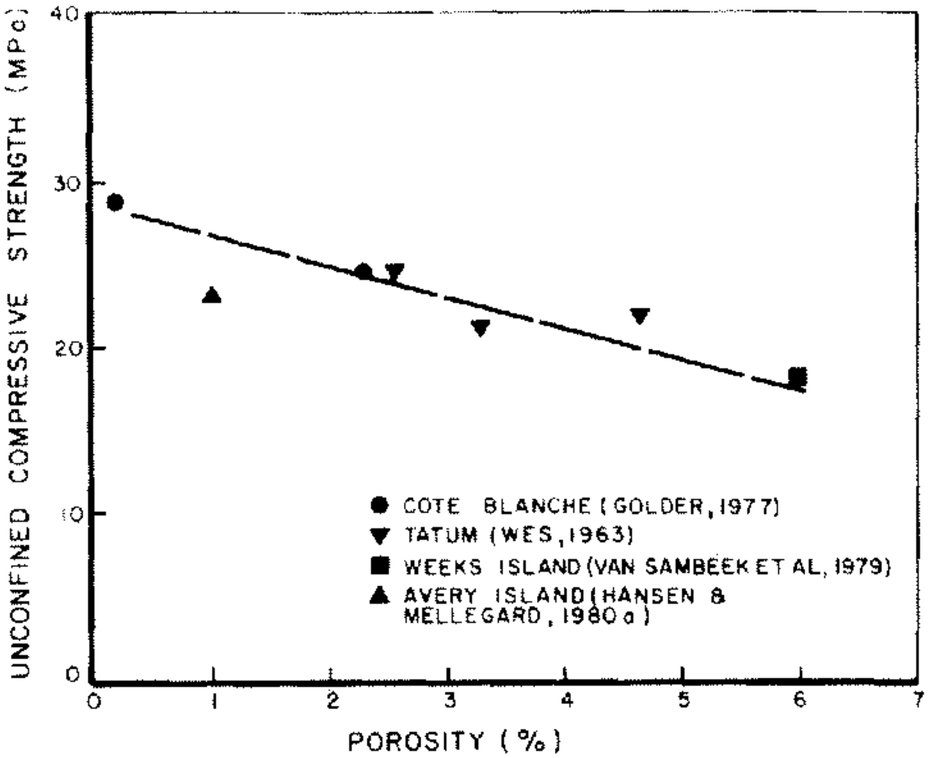


Figure 7. Unconfined Compressive Strength of Dome Salt as a Function of Porosity.

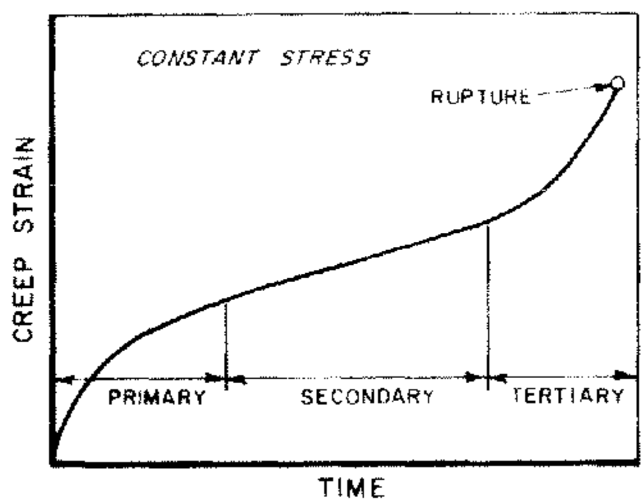


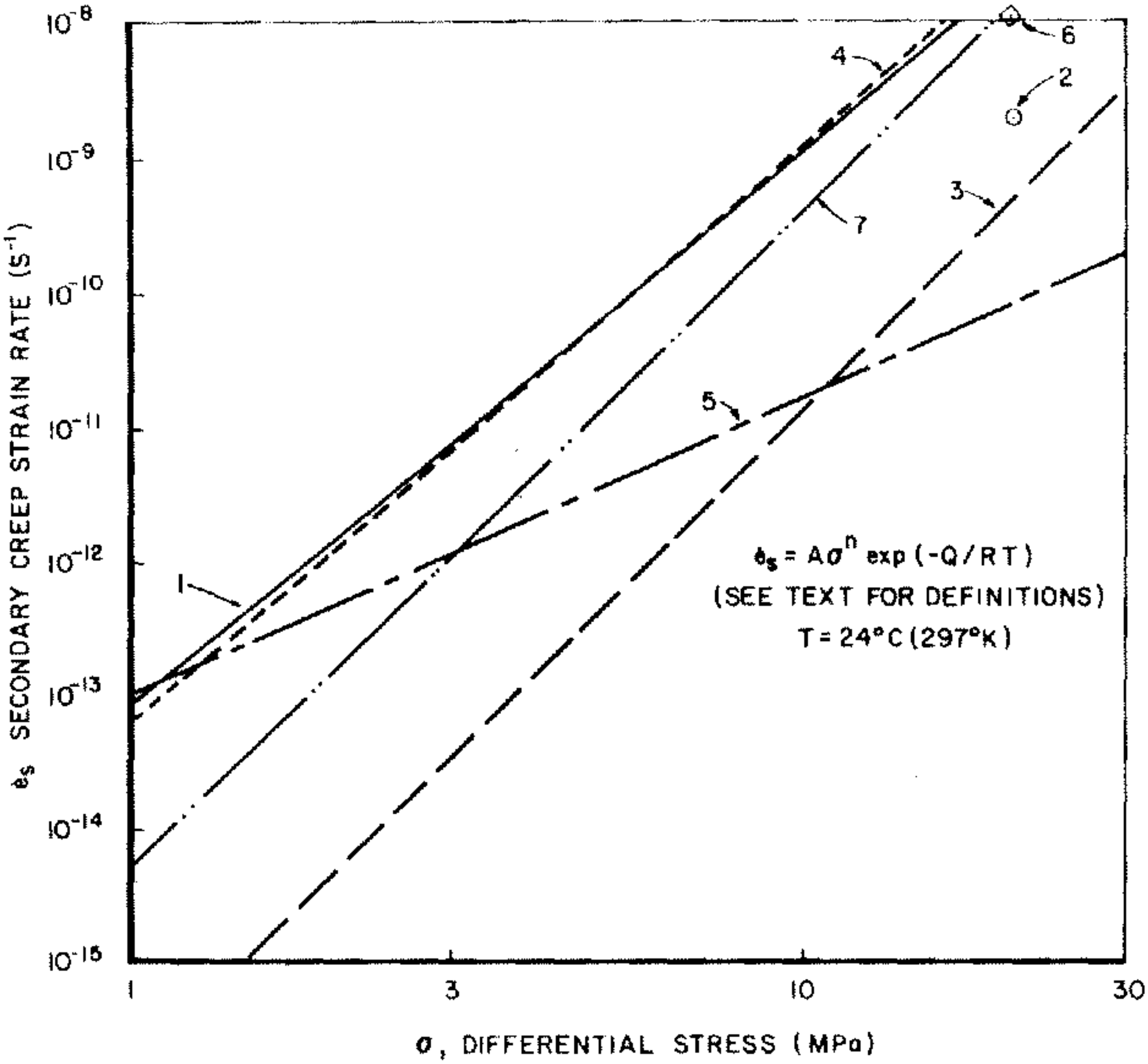
Figure 8. Typical Phases of Creep Deformation.

petrographic examination, and less affected by more obvious differences in mineralogy (within normal limits). Further work is required to investigate the causes of scatter in test results, particularly in the case of creep properties.

ENGINEERING APPLICATIONS

Many of the geologic, hydrologic and thermo-mechanical aspects of salt and salt domes discussed above have important implications for the design, construction and operation of facilities located within salt domes. Before discussing specific applications, it is appropriate to review the important characteristics of domes discussed earlier.

1. Domes vary widely in depth, size, shape and attitude. Overhangs are common, and the area of a dome available for development may be restricted in the depth range of most interest (i.e., 300–1000 m).
2. The top of salt is often flat, particularly in the case of domes with thick caprocks which are indicative



SITE	A	n	Q/R	REFERENCE
	$MPa^{-n}S^{-1}$	–	°K	
1. AVERY ISLAND	6.53×10^{-8}	4.11	4076	MELLEGARD & SENSENY (1981)
2. BRYAN MOUND	*	2.27	*	WAWERSIK ET AL (1980 B)
3. RICHTON	2.60×10^{-2}	5.01	9895	PFIEFLE ET AL (1981)
4. TATUM	1.57×10^{-5}	4.29	5813	CHABANNES (1982)
5. VACHERIE	8.71×10^{-3}	2.22	7569	PFIEFLE ET AL (1981)
6. WEST HACKBERRY	*	*	*	WAWERSIK ET AL (1980 A)
7. WIPP	2.69×10^{-6}**	4.90	6039	HERRMANN ET AL (1980 A)

* INSUFFICIENT TEST DATA TO DEFINE PARAMETERS
** AVERAGE OF 2 VALUES

Figure 9. Creep of Dome Salt as a Function of Stress as Predicted by Parameters Fitted to Secondary Creep Law.

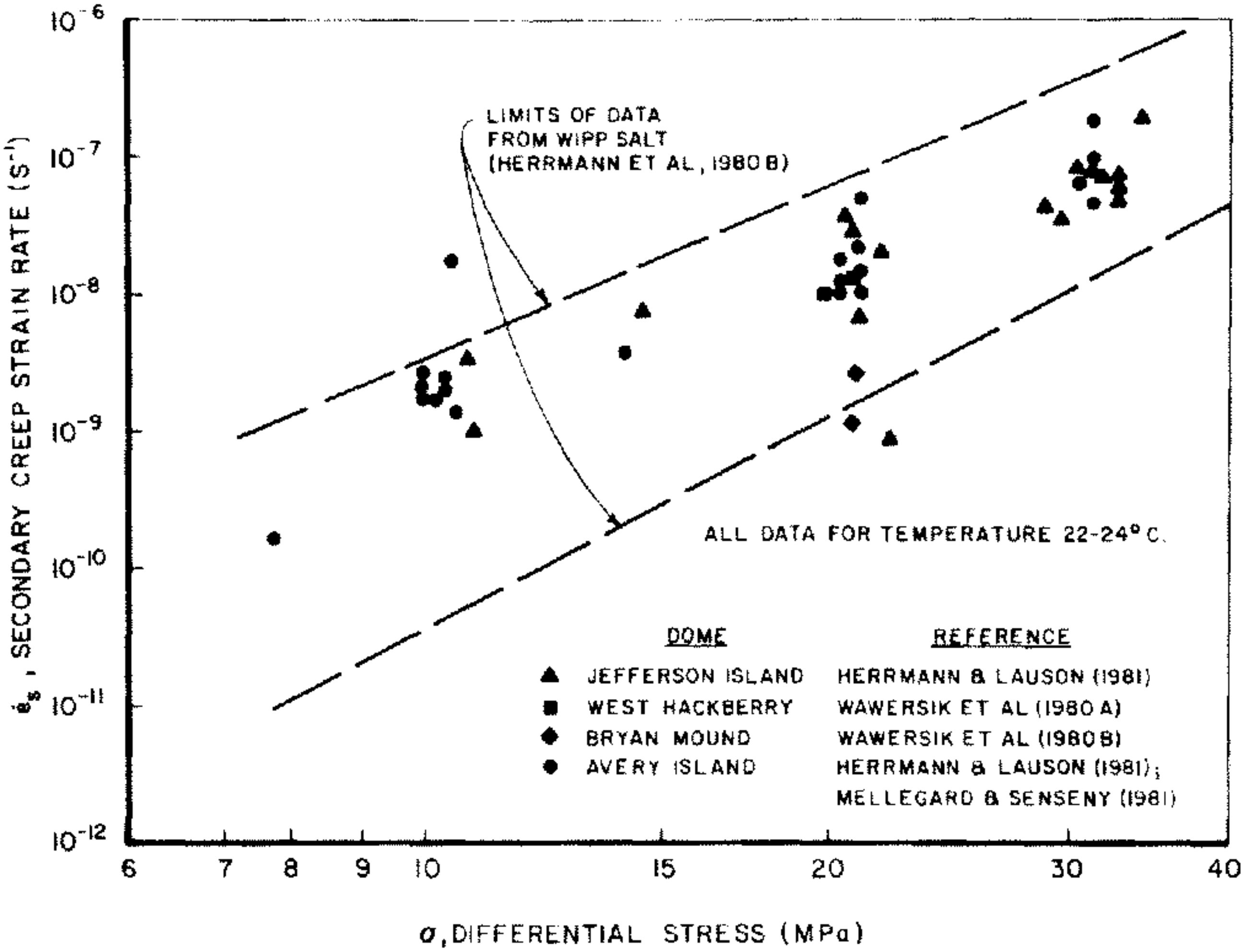


Figure 10. Variation in Secondary Creep Rate for Several Dome Salts in Comparison with Scatter in Data for WIPP Salt.

of extensive dissolution. Domed or irregular surfaces are more likely if the caprock is thin or absent. Extremely irregular surfaces may result from differential movement of adjacent spines or from erosion of a fault separating two spines.

3. The caprock may be as much as 450 m thick but is absent or very thin on many domes. Caprock is typically highly fractured, at least in part, and may contain large volumes of water. Cavities filled with brine or loose anhydrite sand often occur at the salt-caprock interface. Generally, it may be expected that both the caprock overall and the salt-caprock interface will be highly variable in any particular dome.
4. Fractures capable of transmitting meteoric water may extend 150 m or more below the top of the salt.
5. The edge of the salt may be relatively sharply defined, or it may consist of a complex melange of detached blocks of salt and blocks of sediment included within the salt. Within the salt stock, the proportion of impurities and the frequency of anomalous features increase toward the edge of salt.
6. The salt contains 3% to 5% anhydrite with higher concentrations locally. Minor amounts of shale or sandstone and potassium bearing minerals may also be found. Often the impurities are concentrated in bands so that the salt structure is highly anisotropic. The bands are generally steeply dipping, and strikes may be persistent over large areas of a dome.
7. Typically, dome salt exhibits relatively low strength in quasi-static tension and compression, high creep at relatively low stresses and temperatures, very low permeability and high thermal conductivity.
8. Most domes contain small amounts of trapped brine or oil. Small seepages occur immediately after mining but decline and stop usually within a few months. Meteoric water has been known to penetrate up to 150 m into the salt via fractures.

9. Most domes contain gas in the form of intra- or intercrystalline bubbles. The gas may be largely methane, nitrogen or carbon dioxide. In some domes the gas is concentrated in vertically-alligned, cylindrical zones which give rise to outbursts of gas and salt during mining. These outbursts produce chimney-like cavities which can be up to 150 m high. Some domes contain much more gas and are much more prone to large outbursts than others.
10. In some domes impurities and inclusions are concentrated along narrow linear trends which are thought to be shear zones separating adjacent salt spines.
11. Temperatures in domes are higher than those in the adjacent sediments, but are variable from dome to dome. Temperatures may range from 40 to 60°C at 500 m, 55 to 80°C at 1000 m, and 65 to 100°C at 1500 m depth.

Dome Exploration

Because of their irregular shape and heterogenous internal structure, domes are relatively difficult to characterize within typical economic constraints. Fortunately, the general (external) structure of many domes has been explored by oil companies and extensive geological data from drilling and seismic exploration are often available for purchase. Also, many domes have similar internal characteristics that can be predicted, with some degree of uncertainty, from characteristics exposed in mines. Without extensive drilling, however, it may not be possible to recognize (ahead of mine development) adverse features such as major shear zones or high gas content. Fortunately, domes with high gas contents appear to be rare. Also, it is possible in conventional mining to recognize shear zones from boreholes drilled from within the mine and to thereby avoid mining in those zones.

Identification of the lateral limits of the salt dome is critical with respect to the isolation of cavities within the salt and prevention of leaks. It is also important for reasons of salt stability in cases where underground storage areas are close to the edge of the dome. While the top of the dome can be determined with relative confidence by borings and geophysical methods, delineation of the sides of the salt stock is more difficult, both because the salt-sediment interface is frequently ill-defined and irregular, and because borings to great depth are extremely expensive and offer information at only one point. Gravity and high-resolution seismic surveys are useful in outlining the general shape of a dome, but they may not accurately delineate the edge of the dome at depth. Probably the best method for detailed characterization of dome geometry is a radial seismic refraction survey using wells drilled on the flanks of the dome (Musgrave *et al.*, 1960).

Shaft Development and Maintenance

The combination of highly permeable sediments and caprock overlying the salt and the highly soluble nature of the salt sometimes poses difficult problems for shaft sinking and sealing shaft linings in domes. Extensive ground water control techniques (such as freezing or grouting) are often required during shaft sinking; problems may be particularly severe at the salt-caprock interface where sand-filled cavities are often encountered. It is also extremely important that reliable water seals be placed in the salt below the caprock interface to prevent ever increasing water inflow due to dissolutioning of the salt. D'Appolonia (1981) provides a detailed review of shaft sinking and sealing experience from salt mines in the Gulf region, describing methods used to seal linings, and illustrating some of the problems that can occur when insufficient attention is paid to sealing. In one extreme case, at Belle Isle, a shaft was lost when a large leak developed at the base of the concrete liner. Conversely, many shafts have been successfully sunk and sealed in the Gulf region domes, albeit with occasional grouting through the lining to seal leaks, and two shafts (at Avery Island and Weeks Island) have been operational since 1898. In conclusion, water control problems should be anticipated in shaft sinking, but they can be overcome provided that careful attention is given to hydrologic conditions in both design and construction.

Problems with shafts may also result from deformation. In extreme cases there may be differential movement at the caprock-salt or overburden-salt interface leading to misalignment and leakage. In all cases, deep shafts in salt will experience creep closure, if unlined, or high lining pressure, if lined. Problems may be markedly more severe below depths of 600 to 700 m (see below).

Mining and Repository Development

Dome salt at relatively shallow depths generally offers excellent conditions for room and pillar mining with few serious stability problems. Existing Gulf region mines operate routinely with roof spans of 20 m or more (up to 50 m) and with extraction ratios in the range 60% to 70%. Pillar spalling is common and necessitates rock bolting or periodic scaling, but slabbing from the roof is rare. Slabbing may be more likely in the dirty salt associated with shear zones (Kupfer, 1978). Generally, operating mines use roof bolts in maintenance areas and possibly main passageways but not in production areas.

At present, the deepest production level in a Gulf region mine is at less than 500 m depth. Mining conditions will be more severe at greater depths. Creep closure is not known to be a significant problem in any of the existing mines but (as shown below) closure rates will increase dramatically with greater depth due to increasing stresses and temperatures. Outbursts (in domes prone to the phenomenon) may be more severe at greater depths. Also, increasing temperatures at greater depths can necessitate cooling in order to maintain acceptable working conditions. It is noted from Figure 4 that some domes are much hotter than the domes in which mines are currently developed.

Mining can be affected by shear zones. In production mining there is a concern with poor salt quality as well as with potential safety problems due to outbursts or leaks. In a repository, a large outburst or a significant leak would be highly undesirable from a licensing viewpoint. In all applications, shear zones may be recognized and avoided by exploratory drilling ahead of the working face. Tell-tale signs revealed by drilling would include dirty salt (especially sediment inclusions) and high brine or gas content.

A further concern in mining is to maintain an adequate separation from the edge and top of the salt. At present, no reliable method exists for delineating the edge from within the dome, since exploratory drilling to penetrate the edge is imprudent and geophysical methods such as radar are not completely reliable. In several of the mines, however, the approach of the edge is marked by increasing frequency of anomalous features and dirty salt which may serve as general warnings. Current practice in the Gulf region mines is to maintain at least 100 m between workings and both the suspected edge and the top of the dome. Evaluation of domes for nuclear waste storage has used a minimum "buffer zone" of 245 m to determine the area available for development (ONWI, 1982). Selection of an appropriate buffer zone in a salt dome should consider the specific characteristics of the dome, the nature of the facility in the dome, the consequences of hydraulic connection with the outside of the dome and/or physical breaching of the salt, and the confidence or uncertainty which is attached to the suspected edge of the salt.

Solution Cavern Development

Structure within a dome and the nature and proportion of impurities may influence solution mining operations. In cavern development, allowance must be made for anhydrite and insolubles to accumulate in a sump. Allowing for an average anhydrite content of about 5%, and for bulk increase of the insoluble material, the sump volume should be up to 10% of the cavern volume. Moreover, high proportions of anhydrite are undesirable in brining operations because a proportion of the anhydrite is soluble and must be removed from the produced brine. Relatively large proportions of anhydrite may be produced in suspension during the early stages of leaching a cavern when turbulence is high.

The presence of impurities such as anhydrite or sylvite may also affect cavern shape, particularly if the inclusions are concentrated in bands rather than disseminated throughout the halite. If the banding is vertical it might be expected that a cavern will be leached preferentially along the banding, producing an oval horizontal cross section with the long axis aligned along strike. If the banding is steeply dipping, preferential cavern development will occur along strike, and also up-dip due to the effect of the fresh leaching water rising in the cavern. In this case, preferential leaching is most likely to occur close to the roof of the cavern if this is not protected by an oil blanket. Several examples of unusual cavern shapes believed to result from anisotropic geologic structure are described by D'Appolonia (1981) from the Bryan Mound dome. These caverns, and others in the SPR program, provide evidence that unusual cavern shapes and large spans (up to 200 m) do not necessarily lead to stability problems; however, preferential leaching can lead to the possibility for adjacent caverns to coalesce.

As in the case of conventional mining, solution cavern development should maintain a separation of at least 100 m between a cavern and the edge or top of the salt. Cavern design must address the minimum pillar to be maintained between adjacent caverns (Tillerson, 1979) and the anticipated creep closure (see below) which results in pressure build up in the cavern and necessitates periodic bleeding of the system. Pressure build-up also occurs in response to heating of the brine or stored product (Case *et al.*, 1980).

Creep Closure of Underground Openings

The magnitude of creep closure and its importance to the operation of underground facilities in dome salt is highly dependent on the depth of the openings and their use. Creep rates are very sensitive to temperature and stress, both of which increase with depth. In existing salt mines, closure is relatively small and unimportant due to the shallow depth of workings. Similarly, in shallow solution caverns, creep closure is simply an operational concern, requiring occasional relief of pressure build-up and resulting in small losses of storage volume. In deeper mines or caverns, however, the effects of creep closure can be more severe. An important factor influencing the closure rate (and generally limiting the rate) in solution caverns is the internal cavern pressure. In brine-filled caverns, the closure is limited by the head of the brine. Closure will be much greater if the brine is replaced by gas at a lower pressure than the original brine head (see Figure 11).

The effects of creep closure are also significant with respect to nuclear waste storage, where the depths of interest are generally 600 m or more, where significant increases in rock temperature will result from waste emplacement, and where openings will need to be maintained for long periods of time (up to 50 years or more). Paradoxically, high closure rates are disadvantageous in a repository with respect to mining (requiring initial over-excavation or periodic re-excavation), but advantageous with respect to long-term waste isolation. High creep rates should lead to natural healing of any fractures created by excavation of disposal rooms and effective consolidation of crushed salt backfill placed in the disposal rooms (Kelsall *et al.*, 1982).

The rate of creep closure of an underground opening will

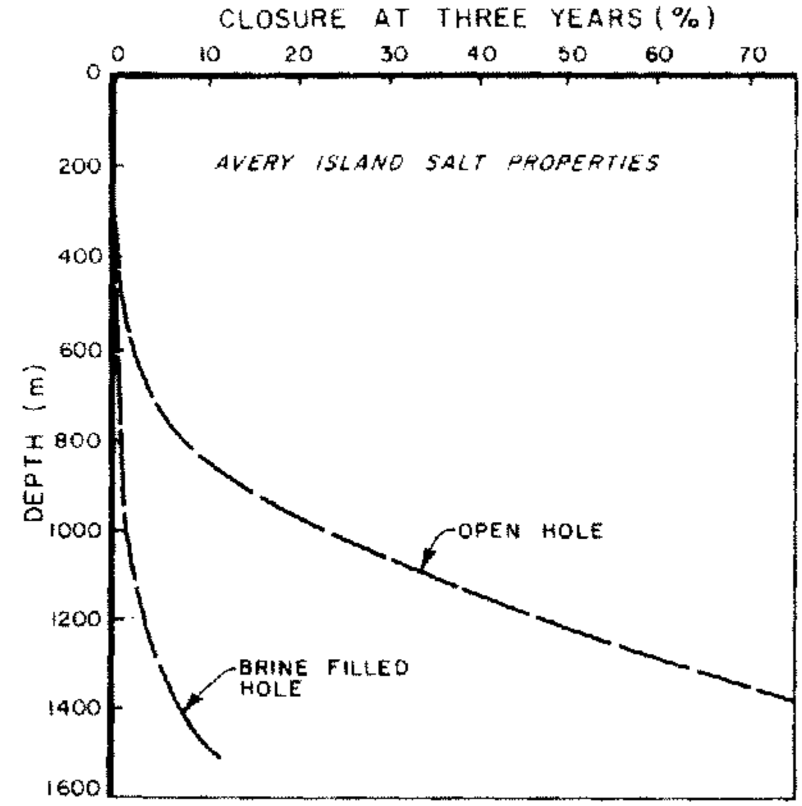


Figure 11. Predicted Closure of a Deep Borehole in a Salt Dome.

depend on depth, temperature, opening shape, internal pressure and salt properties. The effects of these parameters can be investigated by use of closed-form solutions for secondary creep of cylindrical or spherical openings developed by Chabannes (1982) incorporating a creep law of the form given in Equation (2). Figure 11 shows calculated closures for a deep borehole in one type of salt as a function of depth and internal pressure. Increasing temperature with depth is implicit in the analysis, using data (for Rayburn's dome) from Figure 4. Closures would be less for a brine-filled spherical cavern than for the brine-filled borehole but more for a mine with rectangular openings than for the open borehole. As noted previously, creep rates measured in the laboratory vary significantly among different sites. The predicted time for 10 percent closure for a shaft at 610 m depth and a temperature of 34°C, using creep parameters from four domes, is shown in Table 7. It is noted that these predicted closure rates vary by over three orders of magnitude.

It is the authors' opinion that the very wide range in creep rates observed in the laboratory is probably not exhibited *in situ*. This opinion is based primarily on the observed scatter in the test results obtained from a single site. Possibly, creep closure of large volumes of salt in situ tends to "average" the variability. The scatter in the laboratory

TABLE 7

Predicted Times to Reach 10% Convergence for a 3-m Shaft at 610 m Depth Based on Laboratory Creep Data

Dome	Time (years)	References for Creep Properties
Jefferson Island	1	Herrmann & Lauson (1981)
Avery Island	10	Mellegard & Senseny (1981)
Tatum	10	Chabannes (1982)
Vacherie	50	Pfeifle et al (1981)
WIPP*	100	Herrmann et al (1980a)
Richton	3000	Pfeifle et al (1981)

*Bedded salt with extensive data base.

test results points to the necessity for testing a large number of samples from each site (in order to obtain a representative average), and to the necessity to validate analytical predictions of creep closure based on laboratory testing by comparing such predictions with the actual performance of underground openings. This is particularly the case in the NWTS program because of the need to present credible design calculations at the time of licensing. At present, the effects of stress and temperature on creep are reasonably well known. Further work is required to better define and understand the apparent large variation in creep behavior exhibited by different salts.

Isolation

Salt domes have excellent potential for the safe isolation of hazardous wastes. Favorable properties include very low permeability and creep, which tends to seal any fractures which may develop. Adverse properties, as they occur in some domes, may be avoided by prudent design, in particular by maintaining an adequate separation from the top and sides of the dome and by avoiding mining in shear zones. Technical issues regarding the suitability of domes for waste isolation (all of which are being addressed by the NWTS program) include hydrologic and tectonic stability, creep closure rates and the ability to seal man-made boreholes and shafts.

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