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FOSSIL ENERGY

PRELIMINARY TECHNICAL AND LEGAL EVALUATION OF DISPOSING OF NONHAZARDOUS OIL FIELD WASTE INTO SALT CAVERNS

Final Report
June 1996

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Preliminary Technical and Legal Evaluation of Disposing of Nonhazardous Oil Field Waste into Salt Caverns

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Executive Summary

Bedded and domal salt deposits occur in many states. If salt deposits are thick enough, salt caverns can be formed through solution mining. These caverns are either created incidentally as a result of salt recovery or intentionally to create an underground chamber that can be used for storing hydrocarbon products or compressed air or for disposing of wastes. This report evaluates the suitability, feasibility, and legality of disposing of nonhazardous oil and gas exploration, development, and production wastes (hereafter referred to as oil field wastes, unless otherwise noted) in salt caverns.

In 1988, the U.S. Environmental Protection Agency (EPA) published a list of those oil field wastes that were exempt from regulation as hazardous wastes under Subtitle C of the Resource Conservation and Recovery Act (RCRA). EPA's Underground Injection Control (UIC) regulations allow most of those oil field wastes to be injected into Class II UIC wells. Efforts are currently under way to obtain clarification from EPA whether all exempted oil field wastes can be injected into Class II wells. At the state level, only the Railroad Commission of Texas (TRC) has formally authorized disposal of oil field wastes into salt caverns. The TRC has issued permits for six facilities, but as of May 1996, only four of these were active. In April 1996, the TRC released draft proposed amendments to TRC Rule 9, the regulation that governs injection into a formation not productive of oil, gas, or geothermal resources. Ten other states were contacted about their interest in disposing of oil field waste into salt caverns. Many of these states were interested in following the TRC program to see how it worked, but at this time, only New Mexico has received an application for disposal of oil field wastes into salt caverns. There are no apparent regulatory barriers to the use of salt caverns for disposal of most types of oil field wastes at either the federal level or in the eleven states discussed in this analysis.

The types of oil field waste that are planned for disposal in salt caverns are those that are most troublesome to dispose of through regular Class II injection wells, because they contain excessive levels of solids. The solids-containing oil field wastes most likely to be disposed of in salt caverns include used drilling fluids, drill cuttings, completion and stimulation waste, produced sand, tank bottoms, and soil contaminated by crude oil or produced water.

The location and design of waste disposal caverns play an important role in ensuring long-term waste isolation from the surface water or groundwater resources. Hundreds of caverns have been used safely for storing hydrocarbons. The hydrocarbon storage industry has developed useful, detailed standards and guidance for designing and constructing storage caverns that are also appropriate for creating solution-mined caverns for other uses. Several factors should be considered in selecting sites for disposal of oil field wastes in caverns, including distance to populated areas; proximity to other industrial facilities; current and future use of adjacent properties; handling of brine or other displaced fluid; proximity to environmentally sensitive wetlands, waters, and fresh water aquifers; proximity to the salt boundary; and proximity to other existing and abandoned subsurface activities, such as neighboring caverns for brine or hydrocarbon storage. Detailed knowledge of the geology should be supported by adequate documentation. Operators should be able to demonstrate that the caverns they plan to use — either new caverns developed specifically for oil field waste disposal, or existing caverns that are being converted — will remain stable in the future.

Disposal caverns act like large oil/water/solids separators. The solids in the incoming waste settle to the bottom of the cavern while the lighter oils and hydrocarbons rise to the top of the cavern, where they can be removed. When placing waste in a cavern, the cavern space is best utilized by filling evenly and uniformly, with no large voids. One method for emplacing the waste in the cavern is to inject it through the tubing to the bottom of the cavern. Under this scenario, an operator of an oil field waste disposal cavern would inject waste until the end of the tubing is covered or the back pressure from the accumulated waste precludes further injection. At this point, the operator would use a small controlled explosive charge to cut off the end of the tubing further up the cavern. Another Texas operator prefers to inject waste through the tubing/casing annulus into the top of the cavern and allow the waste to settle to the bottom. A third Texas operator has installed two wells in the cavern, one for injection and the other for brine withdrawal. Under any of these waste emplacement scenarios, cavern pressure should be monitored and controlled before the cavern is filled with oil field waste, throughout the waste emplacement cycle, and optimally, for some period of time after waste emplacement has ended.

There is no actual field experience on the long-term impacts that might arise from salt cavern disposal of oil field wastes. The literature contains many theoretical studies that speculate what might happen following closure of a cavern. Although different authors agree that pressures will build in a closed brine-filled cavern due to salt creep (domal salt only) and geothermal heating, they do not specifically address caverns filled with oil field wastes. Caverns filled with oil field wastes having specific gravities greater than that of brine will have a lower likelihood of failure than caverns filled with brine. More field research on pressure buildup in closed caverns is desirable.

Based on this preliminary research, we believe that disposal of oil field wastes into salt caverns is feasible and legal. If caverns are sited and designed well, operated carefully, closed properly, and monitored routinely, they represent a suitable means of disposing of oil field wastes.

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William Barlow	Texas Brine
Charles Chabannes	Sofregaz US Inc.
Dennis Crist	Ohio Department of Natural Resources
Fritz Crotogino	Kavernen Bau- und Betriebs GmbH
Ken E. Davis	Envirocorp Services & Technology, Inc.
H.W. Diamond	Solution Mining Research Institute
Norbert Heitmann	PB-KBB, Inc.
James Linn	Sandia National Laboratories
Joe L. Ratigan	RE/SPEC, Inc.
Robert Thoms	AGM, Inc.
Frank Whelpy	Sonar and Well Testing Service
Scott Whitelaw	Texas Brine

The final report reflects the contributions of each of these persons.

Chapter 1 - Introduction

Content and Purpose of Report

Caverns can be readily formed in salt formations through solution mining. The caverns may be formed incidentally, as a result of salt recovery, or intentionally to create an underground chamber that can be used for storing hydrocarbon products or compressed air or disposing of wastes. The purpose of this report is to evaluate the feasibility, suitability, and legality of disposing of nonhazardous oil and gas exploration, development, and production wastes (hereafter referred to as oil field wastes, unless otherwise noted) in salt caverns.

Chapter 2 provides background information on

- Types and locations of U.S. subsurface salt deposits;
- Basic solution mining techniques used to create caverns; and
- Ways in which salt caverns are used.

Later chapters provide discussion of

- Federal and state regulatory requirements concerning disposal of oil field waste, including which wastes are considered eligible for cavern disposal;
- Waste streams that are considered to be oil field waste; and
- An evaluation of technical issues concerning the suitability of using salt caverns for disposing of oil field waste. Separate chapters present
  - Types of oil field wastes suitable for cavern disposal;
  - Cavern design and location;
  - Disposal operations; and
  - Closure and remediation.

This report does not suggest specific numerical limits for such factors or variables as distance to neighboring activities, depths for casings, pressure testing, or size and shape of cavern. The intent is to raise issues and general approaches that will contribute to the growing body of information on this subject.

Chapter 2 - Background

Types and Locations of U.S. Subsurface Salt Deposits

Figure 1 (from Johnson and Gonzales 1978) shows the location of the major U.S. subsurface salt deposits. There are two types of subsurface salt deposits in the United States: salt domes and bedded salt. Salt domes are large, generally homogeneous formations of salt that are formed when a column of salt migrates upward from a deep salt bed, passing through the overlying sediments. Pfeifle et al. (1995) report that the typical anhydrite (calcium sulfate) content of Gulf Coast salt domes averages less than 5 percent. Salt dome deposits are found in the Gulf Coast region of Texas, Louisiana, Mississippi, and Alabama. Figures 2 through 5 (taken from Jirik and Weaver 1976) show the specific locations of many onshore and offshore salt domes.

Bedded salt formations occur in layers bounded on the top and bottom by impermeable formations and interspersed with nonsalt sedimentary materials having varying levels of impermeability, such as anhydrite, shale, and dolomite. Unlike salt domes, bedded salt deposits are tabular deposits of sodium chloride that can contain significant quantities of impurities. Major bedded salt deposits occur in several parts of the United States.

Although salt deposits occur in many parts of the United States, in most states, the occurrence of salt in the quantities and locations that would promote commercial mining is limited. There are 16 states in which salt occurs in sufficient quantity to be mined by either excavation or solution mining, or recovered through solar evaporation. The states where these major salt deposits occur are: Alabama, Arizona, Colorado, Kansas, Louisiana, Michigan, Mississippi, Montana, New Mexico, New York, North Dakota, Ohio, Oklahoma, Pennsylvania, Texas, and Utah.

Of the states listed above, those with the most significant salt mining operations are: Kansas, Louisiana, Michigan, New Mexico, New York, Ohio, and Texas. These states, either currently or in the future, could contain caverns suitable for oil and gas waste disposal. Pennsylvania contains caverns that are currently permitted for hydrocarbon storage that could potentially be converted to waste disposal caverns. Utah has some potential for future disposal cavern operations, although it is a relatively small oil and gas waste generator. The remaining states have only a limited number of salt production sites and are not likely candidates for future cavern disposal operations.

Formation of Salt Caverns

Salt caverns are formed by injecting water that is not fully salt-saturated into a salt formation and withdrawing the resulting brine solution. Figures 6 and 7 show the main features of salt cavern construction for caverns in domal salt and bedded salt, respectively. These figures are not drawn to scale or intended to show detailed construction features.

The first step in creating a salt cavern is drilling a borehole. Near the surface, the borehole is larger in diameter to allow for installation of several concentric layers of casing, which are cemented in place to protect against contamination of drinking water sources. The outermost layer of casing is known as the surface casing. Typically, it does not extend all the way to the cavern roof. The final casing (or long string casing), which is also cemented, is set at a depth below the top of the salt formation. Generally, a noncemented casing string, the tubing string, is placed in an open hole which has been drilled to a depth approximately where the bottom of the cavern will be, although some interconnected multi-well caverns may not have a noncemented string in each well. In some caverns, two noncemented casing strings may extend to a depth approximately where the bottom of the cavern will be. Under this design scenario, one string is used to inject water and the other is used to withdraw brine.

There are several methods used for developing and shaping the cavern. In the direct circulation method, fresh water is injected through the tubing string, and brine is withdrawn through the annular space between the tubing string and the final casing. In the reverse-circulation method, fresh water enters through the annulus and the brine is withdrawn through the tubing string. A combination of these two methods or other more complicated methods can be used to obtain the desired cavern geometry. API (1994) describes and provides illustrations of these methods.

During cavern formation, a rubble bed of impurities such as anhydrite can form on the bottom of the cavern. Depending on the size of the cavern and the amount of impurities present, more than 50 feet of impurities can sit on the bottom of the cavern (Tomasko 1985).

The petroleum industry has constructed many salt caverns for storing hydrocarbons. In an attempt to provide guidance for designing and operating hydrocarbon storage salt caverns, several organizations have developed standards and guidance documents (CSA 1993, API 1994, and IOGCC 1995). Readers desiring more details on design, location, and construction of salt caverns are referred to these reports.

Use of Salt Caverns

The most common use of salt caverns is production of salt, which in turn, enlarges the caverns. The post-mining uses of caverns are hydrocarbon storage, compressed air storage, and waste disposal.

Hydrocarbon Storage - Salt caverns are commonly used for storing hydrocarbons. The earliest cavern storage for liquified petroleum gas (LPG) in bedded salts occurred in the 1940s, with storage in salt dome caverns beginning in 1951. Some of the products that have been stored are propane, butane, ethane, ethylene, fuel oil, gasoline, natural gas, and crude oil (Querio 1980). In 1975, the U.S. Congress created the Strategic Petroleum Reserve (SPR) program to provide the country with sufficient petroleum reserves to reduce the impacts of future oil supply interruptions. The SPR consists of 62 leached caverns in domal salt with a total capacity of 680 million barrels. The U.S. Department of Energy (DOE) has prepared a plan for, but is not currently pursuing, the development of an additional 250 million barrels of storage capacity.

Waste Disposal - A second use of salt caverns is disposing of various types of wastes. Several examples of actual or proposed waste disposal projects are presented below. These examples are based on limited and not completely up-to-date information from foreign countries. The current extent of cavern waste disposal may be larger now.

United States - In the United States, only limited waste disposal into salt caverns has occurred. In Texas, the Railroad Commission of Texas (TRC) issued six permits between 1991 and 1994 for disposing of oil field waste into salt caverns. As of May 1995, nearly half a million barrels of oil field waste had been disposed of in this manner (Fuller and Boyt 1995). Ten other states with significant solution mining and oil and gas production activity were asked if they currently used salt caverns for disposing of oil field waste. None of these states currently have approved any such disposal projects, although several states reported an interest in the subject. New Mexico has received an application to site and operate a disposal cavern but had made no decision on it as of May 1996. A summary of the contacts with these states is provided in Table 1.

Several proposals for storing hazardous wastes in Texas salt dome caverns were made during the past 10 years, but none have been approved by the Texas state government (Thoms and Gehle 1994). In the early 1980s, a Houston-based waste disposal company proposed to dispose of toxic wastes in the Vinton salt dome in southwest Louisiana. A vertically aligned series of caverns, separated by salt intervals, was to be solution-mined from a single well. The deepest would be mined first, filled with wastes, and then plugged with salt. The next deepest cavern would then be filled and sealed. The process would be continued until the usable salt interval for that well was fully occupied with stacked "mini-caverns". This design was referred to as the "string of pearls" concept and reportedly was patented (Thoms 1995). By minimizing the vertical extent of any particular mini-cavern, pressure differential problems could be reduced.

The DOE constructed the Waste Isolation Pilot Plant (WIPP), an underground repository for radioactive waste, in a bedded salt formation in southeastern New Mexico. Although the WIPP was excavated rather than formed through solution mining, its concept of safely disposing of wastes in a salt formation applies equally well to oil field waste disposal caverns.

The U.S. salt mining industry disposes of impurities removed during the brine purification process into caverns[1].

Canada - In 1995, a U.S. patent was granted to Canadian inventors for a method of refuse disposal in solution-mined salt cavities (Pearson and Alseth 1995), but their process has not yet been used in the United States.

The Province of Alberta has authorized disposal of oil field wastes into several caverns near Edmonton[2].

United Kingdom - In the United Kingdom, various wastes are being disposed of into caverns at the Holford Brinefield (Hoather and Challinor 1994). The brinefield operator is authorized to dispose of 200 tons per day of brine mud solids from the purification of crude brine, and 250 tons per day of alkali wastes from local soda ash production, into salt caverns. The brine displaced from the caverns by the solids is used to slurry additional solids back to the caverns. In addition, the operator is authorized to dispose of organic residues from the production of perchloroethylene, trichloroethylene, and other related chlorohydrocarbons into specially designated caverns that contain alkaline material that will neutralize any free acid in the wastes.

Feasibility studies for disposing of hazardous or other wastes in salt caverns have been conducted in several European countries. Hoather and Challinor (1994) report on a proposal to dispose of contaminated soils, domestic and commercial solid waste (trash), and sewage sludge into the Holford Brinefield in the United Kingdom.

Germany - Germany has adopted technical regulations on hazardous waste management, TA Sonderabfall. These regulations require that all waste that cannot be stored for extended periods above ground without posing a serious threat to the biosphere, even after undergoing treatment, shall be stored underground in suitable geologic formations. The

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[1] Personal communication between Bill Diamond, Executive Director, Solution Mining Research Institute, Deerfield, IL, and John Veil, Argonne National Laboratory, Washington, DC, on August 22, 1995.

[2] Personal communication between Brenda Austin, Alberta Energy and Utilities Board, Calgary, Alberta, Canada, and John Veil, Argonne National Laboratory, Washington, DC, on May 17, 1996.

German government and the Lower Saxony Company for the Final Disposal of Hazardous Waste (NGS) co-sponsored a study of the feasibility of storing hazardous waste in salt caverns (NGS date unspecified, Crotogino 1990). The TA Sonderabfall requires that brine be removed from the caverns before emplacing wastes. The NGS study found that by adapting existing technologies for waste conditioning, waste emplacement, and cavern engineering, the requirements of TA Sonderabfall could be

met. At this time, however, no hazardous wastes have been disposed of in German salt caverns.

Crotogino (1994) reports that salt-bearing drilling fluids and cuttings arising from deep drilling for natural gas, oil, and salt caverns are disposed of in salt caverns. At the time Crotogino presented this paper, projects were in the planning stage for disposing of various mineral bulk residues (e.g., contaminated soil, ashes, dusts, and sand blasting residues) in salt caverns. More recently, Germany is planning to dispose of sediments contaminated with mercury from the harbor in Hamburg into salt caverns[3].

Netherlands - Wassman (1983) reports that the Dutch have disposed of wastes from a brine purification plant in a salt cavern. At that time, the Dutch were making plans to dispose of drilling fluids and drill cuttings in salt caverns. Concentrated magnesium chloride brine has also been stored in caverns.

Mexico - In Mexico, sulfate purged from salt evaporators is being disposed of into salt caverns[4].

[3] Personal communication between Fritz Crotogino, Kavernen Bau- und Betriebs-Gmbh, Hannover, Germany, and John Veil, Argonne National Laboratory, Washington, DC, on August 25, 1995.

[4] Personal communication between Jose Pereira, PB-KBB, Houston, TX, and John Veil, Argonne National Laboratory, Washington, DC, on October 3, 1995.

Chapter 3 - Regulatory Considerations

Extent of Evaluation

This chapter evaluates the state and federal environmental requirements as they apply to disposal of oil field wastes into salt caverns. No attempt is made to encompass all types of permits, licenses, or approvals that must be obtained by an operator, including zoning approvals, mineral rights, and construction, safety, and fire code requirements.

Description of Nonhazardous Oil Field Wastes

On July 6, 1988, the U.S. Environmental Protection Agency (EPA) issued a regulatory determination that exempted wastes from the exploration, development, and production of crude oil, natural gas, and geothermal energy from regulation as hazardous wastes under the Resource Conservation and Recovery Act (RCRA) Subtitle C (53 FR 25477). The list of wastes exempted from RCRA Subtitle C is reproduced in Table 2. On March 22, 1993, EPA issued clarification of the 1988 determination, adding that many other wastes that were uniquely associated with exploration and production operations were also exempted from RCRA Subtitle C requirements (58 FR 15284). The clarification of the RCRA exemption restates EPA's position that wastes derived from treatment of an exempted waste generally remain exempt, and that off-site transportation does not negate the exemption. Some wastes derived from treatment of an exempt waste may not be exempt, however. For example, if a treatment facility uses acid to treat an exempt waste, the waste material derived from the exempt waste remains exempt, but the spent acid is not exempt.

EPA has emphasized the need to work with states to encourage changes in their regulations to improve management of oil and gas exploration and production wastes. For example, although RCRA Subtitle C specifically exempts produced water, drilling fluids, and "other wastes associated" with exploration, development, and production activities, most state regulations exempt produced water and drilling fluids from hazardous waste regulation (allowing for their disposal into Class II injection wells) but are often silent on the requirements for the "associated wastes". EPA specifically identified in its 1988 regulatory determination many "associated wastes" that are exempt under RCRA Subtitle C (see Table 2).

Consideration of Salt Caverns Used for Disposing of Oil Field Waste as Class II Injection Wells

Under the authority of the Safe Drinking Water Act (SDWA), EPA established regulations for the Underground Injection Control (UIC) program. All injection wells are assigned to five classes. Salt caverns used for disposing of oil field waste are Class II wells. States seeking authority to administer the UIC program can seek primacy in two ways. Under §1422 of the SDWA, states must demonstrate that their state regulations are at least as stringent as those adopted by EPA. To provide greater flexibility for states administering Class II programs, Congress added §1425 to the SDWA, which requires states seeking delegation to have an underground injection program that meets the requirements of §1421(b)(1)(A)-(D) and represents an effective program to prevent underground injection that endangers drinking water sources. A brief discussion of the relevant federal UIC regulations follows. References to state responsibilities in the following sections are those that would apply to states seeking delegation under §1422.

40 CFR Part 144 - These regulations establish the minimum requirements for the UIC program. Each state must meet these requirements in order to obtain primary enforcement authority for the UIC program in that state. These regulations also are part of the UIC programs in states where the program is administered directly by EPA. The SDWA provides that all underground injections are unlawful and subject to penalties unless authorized by permit or by rule. Part 144 sets forth the permitting and other program requirements that must be met by UIC Programs, whether run by a state or by EPA. Class II injection wells are defined as

> "wells which inject fluids:
>
> (1) Which are brought to the surface in connection with natural gas storage operations, or conventional oil or natural gas production and may be commingled with waste waters from gas plants which are an integral part of production operations, unless those waters are classified as a hazardous waste at the time of injection.
>
> (2) For enhanced recovery of oil or natural gas; and
>
> (3) For storage of hydrocarbons which are liquid at standard temperature and pressure." (40 CFR 144.6(b))

EPA defines well as a "bored, drilled or driven shaft, or a dug hole, whose depth is greater than the largest surface dimension," and fluids as "any material or substance which flows or moves whether in a semisolid, liquid, sludge, gas, or other any other form or state" (both from 40 CFR 144.3).

The requirements in Part 144 that may affect the proposed use of salt caverns as Class II injection wells for disposal include the prohibition of movement of fluid into underground sources of drinking water (§144.12) and the compliance with a plan for plugging and abandonment of the well which meets the requirements of §146.10.

40 CFR Part 145 - These regulations specify the procedures EPA will follow in approving, revising, and withdrawing state programs under the UIC provisions of the SDWA, and include the elements that must be part of submissions to EPA for program approval and the substantive provisions that must be present in state programs for them to be approved. EPA has established UIC programs in states that do not comply with elements of a state program submission set forth in §145.22. When a state UIC program is fully approved by EPA to regulate all classes of injections, the state assumes primary enforcement authority under section 1422(b)(3) of the SDWA. States are not precluded, however, from omitting or modifying any provisions to impose more stringent requirements.

40 CFR Part 146 - These regulations set forth technical criteria and standards for the UIC Program. Part 146 standards in the following areas may affect the proposed use of salt caverns as Class II injection wells for disposal: the area of review for each injection well, mechanical integrity, plugging and abandonment, construction of new and some existing wells, and operating and monitoring.

Comparison between RCRA and UIC Regulations

Salt caverns used for disposing of nonhazardous oil and gas waste brought to the surface in connection with conventional oil and natural gas production activities clearly would fit into the section (1) category of Class II wells. Most, but not all of the wastes exempted by the 1988 RCRA regulatory determination would meet the UIC program's "in connection with" oil and gas production criterion. Some wastes (e.g., hydrocarbon-contaminated soil) would not meet the UIC criterion, however. Although EPA's description of wastes that are "uniquely associated" with oil and gas production under RCRA (58 FR 15284) cannot be clearly applied to determining whether such wastes have been brought to the surface "in connection with" oil and gas production under the UIC Class II regulations, the waste in question (i.e., the soil) has been contaminated by wastes that have been brought to the surface. In February 1996, the Ground Water Protection Council asked EPA to clarify that all exempted oil field wastes can be injected into Class II wells. As of May 1996, EPA had not issued the requested clarification.

This potential gap is somewhat clarified by a draft 1993 memorandum from James Elder, then EPA's Director of the Office of Ground Water and Drinking Water (the part of EPA that oversees the UIC program), to EPA Regional Water Management Division directors (Elder 1993). In that memorandum, EPA headquarters states:

> "The key concepts that have been used by the UIC program to determine whether waste fluids could be injected in Class II wells were that they had to be **non hazardous** and **integrally associated** with oil and gas production .... we believe that all exempt E&P [exploration and production] wastes under RCRA can be injected in Class II wells as long as their physical state allows it."

Although that memorandum has apparently never been issued in final form, it has been used as the basis of at least one letter from EPA Region VI to the State of Louisiana outlining the policy on waste types eligible for Class II well disposal (Knudson 1993). In that letter, Myron Knudson, the Director of Region VI's Water Management Division, states:

> "Under the new guidance, all exploration and production (E&P) wastes exempted under Section 3001(b)(2)(A) of the Resource Conservation and Recovery Act (RCRA) will be eligible for injection into Class II disposal wells."

EPA's position from 1993 is clearly indicated, but since the guidance from EPA headquarters is in draft form, clear guidance is needed to determine which types of exploration and production wastes may be disposed into Class II wells. Of course, those wastes determined by EPA not to be exempt from RCRA Subtitle C (i.e., hazardous oil and gas production wastes) could not be legally injected into a salt cavern permitted as a Class II injection well. The section (1) category of injection well is often referred to in state regulations as a "disposal well."

State UIC Regulations

As described earlier, regulatory agencies in eleven oil-producing states where salt caverns exist were consulted with regard to the possible use of salt caverns for disposal of oil field wastes. Most of the contact persons in each state felt that, were salt caverns to be used for this purpose, they would be considered Class II injection wells. However, with the exception of one state, Texas, these state officials said that salt caverns were not being used in such a manner in their state. Moreover, most said that such an idea has never been formally proposed in their state. These same officials, however, generally thought there were no existing provisions in their states' Class II injection well or other regulations which would specifically prohibit the practice of disposing of oil field wastes in salt caverns. Three of the eleven states, Michigan, New York, and Pennsylvania, do not have "primacy" to administer and enforce their own Class II injection well programs. Applicants in these states must therefore apply directly to EPA for Class II permits.

Relevant Differences from EPA UIC Regulations - In the three states that do not have primacy, Michigan, New York, and Pennsylvania, a person wishing to receive a permit to use salt caverns as Class II injection wells for disposal of oil field wastes must comply with the applicable EPA regulations[5]. Ohio's oil and gas law states that the Ohio injection well regulations are to be

[5] Michigan, New York, and Pennsylvania require state-level permits, in addition to UIC permits issued by EPA, to drill or alter an existing oil or gas well. Michigan requires a permit to drill a well for disposal of brine or other oil field wastes (Michigan Act 61, §319.23. Pennsylvania requires the applicant to submit a copy of the EPA UIC permit and EPA UIC application, as well as the related documentation required

interpreted as no more stringent than the SDWA UIC regulations, unless a stricter interpretation is essential to ensure that underground sources of drinking water will not be endangered (Ohio Revised Code §1509.22(D)). Oklahoma's salt deposits are not suitable for extensive solution mining or salt cavern disposal, so no detailed analysis of that state's UIC regulations was conducted.

In the six remaining states whose regulations were analyzed, the applicable state regulations may vary from EPA regulations in the extent to which they would allow salt caverns to be used for oil field waste disposal. The relevant provisions of those states' regulations are discussed below, followed by a discussion of the Texas program.

Kansas - The Kansas General Rules and Regulations for Conservation of Crude Oil and Natural Gas set forth permit requirements for injection and disposal wells (§82-3-400 through 499). Section 82-3-101 defines disposal well as a well in which those fluids brought to the surface in connection with oil and natural gas production are injected for purposes other than enhanced recovery. The definition of fluid is identical to that in the EPA UIC regulations.

A possible impediment to the use of salt cavern disposal wells in Kansas is the existence of well location and spacing requirements (§82-3-108 and 109). Although these requirements were not specifically mentioned as impediments in discussions with the Kansas contact person, this official did express concerns about the additional dissolution of cavern walls that might occur if caverns are used for disposal of oil and gas waste. The dissolution of the caverns could affect the spacing between caverns.

It should be noted that §82-3-100 allows the state to grant an exception to any of these oil and natural gas conservation regulations.

Louisiana - The Louisiana Department of Natural Resources Regulations, §43:XIX.129, contain Class II injection well requirements, including wells for disposal of nonhazardous oil field waste generated from drilling and production of oil and gas wells at §43:XIX.129.M, which apply to the disposal of nonhazardous oil and gas waste by a commercial facility. These regulations define nonhazardous oil field waste (NOW) similarly to the description of wastes suitable for disposal under EPA's Class II injection well regulations. The Louisiana regulations also list all wastes included in the definition

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by EPA. Pennsylvania requires the applicant to submit both a control and disposal plan and an erosion and sedimentation plan, in order to comply with state water pollution, erosion, and erosion sedimentation control regulations (Pennsylvania Code, Title 25, §78.18). New York requires a "conversion permit" for the construction involved in converting a solution-mining or storage well to a disposal well (New York Department of Environmental Conservation Regulations, Title 6, Chapter V, Subchapter B, Part 552).

of NOW. The wastes listed are similar to those listed in EPA's 1988 regulatory determination on the exemption of oil and gas wastes from RCRA Subtitle C.

As in the Kansas regulations, Louisiana's regulations require the subsurface geology of any proposed injection zone to exhibit adequate thickness and areal extent. Dissolution of salt cavern disposal well walls may impede compliance with this requirement.

Mississippi - Mississippi Rule 63, governing underground injection wells, contains a description of the materials that may be injected into Class II disposal wells that is identical to that contained in 40 CFR Part 144 for Class II disposal wells. Most of the requirements of Rule 63 that are stricter than EPA's regulations are administrative and monitoring requirements. Rule 63 also contains criteria for establishing minimum distances between wells, which are not required by EPA regulations. Such minimum distance requirements would need to be carefully considered when siting caverns for disposal of the oil and gas wastes. Incoming wastes that were not fully saturated with salt could dissolve the walls of the caverns, thereby affecting the wall thickness[6]. Rule 63 does allow for exceptions to be granted for any construction or operating requirement contained in the Rule.

New Mexico - The New Mexico Oil Conservation Division's Rules 701-711 set forth the new requirements for Class II injection and disposal wells that allow disposal of saltwater and produced water in Class II disposal wells. The Rules contain construction, operating, testing, and monitoring requirements. The New Mexico contact person felt that the process for disposal of nonhazardous oil and gas wastes into salt caverns was unclear, but that it would likely be regulated under the Class II well regulations. He stated that certain requirements of the New Mexico regulations are more stringent than the EPA regulations, including the area of review, injection pressure, and construction requirements. He could not foresee, however, that these stricter requirements would be more difficult to comply with for operators of salt cavern disposal wells than for operators of other Class II disposal wells. He stressed, however, that his opinion was qualified due to uncertainty about the process[7].

North Dakota - The North Dakota Injection Control Regulations, Chapter 43-02-05, contain a definition of underground injection identical to that contained in 40 CFR Part 144 for disposal wells. There do not appear to be any requirements in the North Dakota

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[6] Personal communication between Fred Hille, State Oil and Gas Board; Jackson, MS, and Mary Raivel, Argonne National Laboratory, Washington, DC, on August 23, 1995.

[7] Personal communication between David Catanach, New Mexico Oil Conservation Division, Santa Fe, NM, and Mary Raivel, Argonne National Laboratory, Washington, DC, on August 31, 1995.

regulations beyond the minimum EPA requirements that would impede the use of salt caverns as Class II injection wells in North Dakota. However, North Dakota's UIC coordinator explained that salt formations in the state are very deep. Consequently, the engineering problems and associated costs suggest that cavern disposal is probably not a realistic option for North Dakota[8].

The Texas Program - The Texas regulation applicable to use of salt caverns as Class II injection wells for disposal of nonhazardous oil and gas waste, Texas Statewide Rule 9 (§3.9), allows disposal of saltwater or other oil and gas waste by injection into a porous formation not productive of oil, gas, or geothermal resources. The TRC is the agency responsible for administering this regulation. To date, six permits under Rule 9 have been issued for disposal of oil field waste in salt caverns. Rule 9 also sets forth monitoring and reporting requirements, which require the operator to monitor the injection pressure and injection rate of each disposal well on at least a monthly basis. There are also requirements for pressure testing the well, the area of review, casing, special equipment, and plugging of wells.

In April 1996, the TRC released draft proposed amendments to Rule 9 that set forth requirements specifically for disposal of oil and gas wastes in solution-mined salt caverns. Cavern disposal wells may be created, operated, or maintained only in impermeable salt formations so that they do not cause surface water or groundwater pollution or danger to life or property. The draft proposed amendments would require the applicant to submit

- A list of the types and maximum volume of the oil and gas wastes to be disposed of;
- Geologic information concerning the overlying and surrounding formations and the size and shape of the cavern;
- A list of all wells within one-quarter mile of the proposed cavern disposal well that penetrate the salt formation and any adjacent disposal, mining, or storage cavern wells or caverns;
- Topographic maps;
- An operating plan that describes facilities, equipment, brine management, and cavern monitoring;

[8] Personal communication between Charles Koch, North Dakota Industrial Commission, Oil and Gas Division, Bismark, ND, and John Veil, Argonne National Laboratory, Washington, DC, on May 14, 1996.

- A closure plan that addresses monitoring of pressures after shut-in and demonstrates that post-plugging pressure increases will not affect the well's ability to confine the injected fluids; and

- Financial security information.

The draft proposed amendments also describe standards applicable to operation of a cavern disposal well, including

- Maintaining records of the fluids used to slurry the wastes into the cavern and the type, volume, and characteristics of the wastes that are injected;

- Setting maximum injection pressure of a cavern disposal well; and

- Establishing monitoring, financial security, and recordkeeping requirements.

The amendments also establish testing, monitoring, surveying, and closure requirements for cavern disposal wells.

Regulatory Conclusions

Other than the draft proposed amendments to the Texas regulations, there are no specific regulations addressing disposal of oil field wastes in salt caverns at either the federal level or in the states discussed in this analysis. EPA's Class II well requirements do not specifically address oil and gas wastes generated on the surface (not brought to the surface in connection with conventional oil and natural gas production activities). It would be useful if EPA would explicitly address such wastes under the UIC program. Some of the types of wastes that are currently going into the four operating Texas cavern disposal wells are in this category (e.g., contaminated soils).

Another potential barrier to allowing the practice of disposal of oil field wastes in salt caverns is the general nature of a state's existing applicable regulations. States would need to make a decision about whether to allow the practice under existing regulations, amend the existing regulations to more specifically address and permit salt cavern disposal wells, or amend the regulations to specifically prohibit the practice.

Given the current level of support at the state level for the use of salt caverns for disposal of oil field waste, and the general consensus that this practice is possible and feasible, it seems entirely reasonable that oil-producing states in which salt caverns are located could allow salt cavern disposal of oil field waste where appropriate. Moreover, these states could use the Texas salt cavern disposal program as a model. Contact persons from several of the other states indicated that they were interested in seeing how the TRC program worked out.

Chapter 4 - Types of Oil Field Wastes Suitable for Cavern Disposal

Chapters 4-7 present technical issues associated with disposing of nonhazardous oil field wastes into salt caverns.

Types of Wastes to be Accepted

The types of oil field waste proposed for disposal in salt caverns are those that are most troublesome to dispose of through regular Class II injection wells because they contain higher levels of solids. Wastes containing water that is not fully saturated with salt may increase the size of caverns because the unsaturated water will leach salt from the cavern walls. The presence of fresh water in wastes should not preclude their disposal in salt caverns, but the operator must account for the increased volume of the cavern and what effect it will have on such cavern siting parameters as distance to adjacent caverns and roof span or thickness. The solids-containing oil field wastes most likely to be disposed of in salt caverns include

- Used drilling fluids,
- Drill cuttings,
- Completion and stimulation waste,
- Produced sand,
- Tank bottoms, and
- Crude oil- or salt-contaminated soil.

Each of these wastes is described below.

Used Water-Based Drilling Fluids - Water-based fluids are suspensions of drilling fluid additives and formation solids in water. They usually contain many of the following ingredients: barite, clay, chromium lignosulfonate, lignite, polymers, caustic soda, and formation solids. They may also contain low concentrations of specialty chemicals added to treat a specific problem (e.g., aluminum stearate - defoamer, zinc carbonate - hydrogen sulfide scavenger). Water-based fluids may also contain 0 - 5 percent emulsified diesel or mineral oil. The water in water-based fluids may be relatively fresh or may contain high concentrations of sodium, potassium, or calcium chloride.

Used Oil-Based Drilling Fluids - Oil-based drilling fluids are water-in-oil emulsions. They contain a base oil (diesel or mineral oil), barite, clays, emulsifiers, water, calcium chloride, lignite, and lime. Oil-based fluids are more expensive than water-based fluids and are normally recovered and cleaned up for reuse; however, in some situations salt cavern disposal might be economically viable. Oil-based fluids are dense, viscous, exhibit low vapor pressure, do not dissolve cavern walls, and are immiscible with brine. One would expect excellent cavern integrity and minimum disturbance of the displaced brine from this type of waste.

Drill Cuttings - Cuttings consist of formation solids (shale, sandstone, chert, etc.) and associated drilling fluid liquid (water or oil and fluid additives - barite, clay, lignite, polymers, etc). Cuttings contain trace amounts of heavy metals; however, these are present as insoluble inorganic salts in concentrations comparable to those found in surface soils.

The nature of the associated fluid is the most important characteristic that distinguishes cuttings for disposal. Thus, cuttings may be classified as either water-based or oil-based. Water-based cuttings may be further classified as salt-water-based or fresh-water-based. Normally, fresh-water-based cuttings would not be candidates for cavern disposal, because in most cases it is permissible to dispose of them on site either through land farming or direct pit closure.

Waste from Completion and Stimulation Operations - Various completion and stimulation processes on oil and gas wells result in solids-containing waste. Excess cement after setting plugs or cementing casing may result in cement waste. Washing sand out of tubing will result in silicon dioxide and other formation solids. Acid stimulation wastes may contain solids or neutralized wastes may deposit solids. There are a number of other, similar waste sources. All these would be candidates for disposal in a salt cavern.

Produced Sand - Many formations composed of sandstone break down, and fine particles of the formation are produced along with oil, gas, and water. These siliceous materials are much heavier than the liquid portions of the produced stream and settle out in piping, separators, and other treatment vessels. This material is distinct from tank bottoms because it collects rapidly in large amounts and is fairly uniform in composition, mostly as particles of silicon dioxide (sand). Other small impurities in produced sand can be water-formed scales and clays. Water-formed scales tend to contain radium as a co-precipitant in the scale. At times, the naturally occurring radioactive materials (NORM) concentration can be high enough to cause this waste to fall under NORM waste disposal regulations.

Tank Bottoms - Solids accumulate in the bottom of tanks and treating vessels. These solids usually contain oil and are dispersed in a water continuous phase. The solids content is composed of clays and other formation fines, corrosion products such as iron sulfide and iron oxide, water-formed scales such as calcium carbonate or calcium sulfate, and bacterial bodies (biomass). Trace constituents might include treating chemicals, live bacterial cultures, dissolved gases such as carbon dioxide, and hydrogen sulfide. Water-formed scales tend to contain radium as a co-precipitant in the scale. At times, the NORM concentration can be high enough to cause this waste to fall under NORM waste disposal regulations.

In physical form, such wastes range from soft, flocculent materials composed of small amounts of solids dispersed in water and oil to hard, cemented masses that are almost entirely solid materials. Typically, this waste is a watery sludge, and it is collected and transported by vacuum truck. Solids entrained in the waste are of small particle size and may be almost neutrally buoyant in water.

Crude Oil-Contaminated Soil - Surface soil may become contaminated with crude oil because of spills or leaks. Crude oil-contaminated soil would be a potential candidate for cavern storage if reclamation were not economically feasible.

Salt-Contaminated Soil - Surface soils may become contaminated with salt due to brine or produced water spills or leaks. Salt-contaminated soil would be a potential candidate for cavern storage if reclamation were uneconomical.

Monitoring and Recordkeeping Considerations

It is the best interest of both the regulator and the operator to know what types of wastes have been placed in the disposal cavern. This report does not propose specific monitoring requirements; rather the reader is referred to IOGCC (1994), which puts forth criteria that are intended to guide states in assessing and improving their regulatory programs for oil field waste management. While the IOGCC criteria do not specifically apply to disposal of oil field wastes by injection (which logically includes cavern disposal), they should be considered as a useful starting point for establishing monitoring requirements. In particular, Section 5.2 - Waste Characterization should be consulted.

It is appropriate to maintain long-term records of the source, quantity, and type of each batch of waste brought to the disposal facility.

Chapter 5 - Cavern Design and Location Considerations

Hundreds of salt caverns have been constructed and operated around the world. Most of these have been structurally sound and completely free from leakage or collapse. If cavern failure does occur, however, it can lead to contamination of surface water and groundwater. This chapter discusses several potential failure modes or areas of concern and approaches for mitigating or at least addressing the concerns.

Potential Failure Modes

Salt Creep - Salt is a material that creeps or flows under stress. Creep closure is an active process in any salt cavity where stresses or pressure differentials exist. Scientists have studied the behavior of rock salt, and the subject remains a topic of investigation. Agreement exists among most scientists that salt behaves as a fluid (it flows under even small deviatoric stresses) and that the creep rate of a cavern is a highly nonlinear function of its internal pressure and is strongly influenced by temperature (Berest and Brouard 1995). These factors provide for the "self-healing" of salt. In caverns used for gas storage, for example, fractures resulting from excessive operating pressures will close when the pressures return to normal. However, creep also results in loss of volume or closure of caverns. The effort required to obtain site-specific data may be very large, and modeling of salt is quite specialized, although models are available to do these types of calculations.

Cavern Roof Collapse and Subsidence - Cavern roof collapse would most likely occur in caverns with minimal or no salt roofs or other weight-supporting roof structure, in caverns with excessive roof spans, or in caverns with minimal internal pressure. Under such conditions, lithostatic pressure (the pressure attributable to the weight of the overlying rock) could exceed the load-carrying capability of the roof support and the roof could collapse. Collapse of a cavern roof may result in sudden major subsidence at the surface and formation of sinkholes extending for hundreds of feet around the cavern well. Nieto-Pescetto and Hendron (1977) suggest that sinkholes are less likely to occur when the thickness of the overburden is greater than ten times the thickness of the salt layer.

Failure will also depend on size of the roof span and strength of the strata overlying the salt. As salt is leached from the walls or roof of the cavern, load is transferred to the strata above the salt, increasing the stress in these less ductile layers. The cavity roof begins to fail when the stress exceeds the strength of these layers. There are several documented cases of cavern roof collapse, including solution-mined brine caverns in Grosse Ile, Michigan, and solution-mined caverns in Windsor, Ontario (Coates et al. 1983). While the potential for roof collapse exists for any cavern, the likelihood of roof collapse is very small for most caverns.

Impacts from a general collapse would occur from the dispersion of the waste that had been disposed of in the cavern or from displaced brine. The final environmental impact statement (EIS) for the Seaway Group Salt Domes prepared for the SPR described the process of general collapse for an oil-filled cavern (DOE 1978). If the waste materials in the cavern were in a liquid or semi-liquid form, the process described by DOE for collapse into an oil-filled cavern could be similar for collapse into a waste-filled cavern, assuming the properties of the waste were similar to the properties of the oil. In the DOE collapse model, the contents (a nearly incompressible fluid such as brine or oil) would be displaced volume for volume by the falling caprock and overlying sediment. If the entire column of sediment above a cavern entered it in a manner analogous to a piston in a cylinder, and if the cavern contents were completely displaced by percolation through the sediments of the piston, rather than compressed, there would be a surface depression equal in volume to the original cavern, filled but not overflowing with the displaced fluid.

A more realistic result would reflect various mechanisms (imperfect packing of falling particles, adsorption, absorption, dissolution, and trapping of the displaced fluid), which would reduce the amount of fluid that would continue to rise through the cone of influence and emerge to the surface or that would migrate into aquifers between the surface and the top of the cavern. Under these mechanisms, the oil would probably reach the surface as small seeps, and as sediment settled into the place formerly occupied by the oil, a small surface depression would form. Subsidence could also occur without surface emergence of oil. Using the piston analogy, and assuming that the oil percolates up through water-saturated sediments that have zero empty pore space, there would be a volume for volume displacement of oil, and the combined volume of waste and saturated sediments would remain constant. If the oil moved up from the saturated layer into the empty pores of an unsaturated layer, the volume of the unsaturated layer would remain constant as long as the oil filled only empty space. Oil would not emerge on the surface until all the pore space near a potential seep was filled with oil. This would permit the possible formation of an oil slick on top of the water table surface in the unsaturated layer (DOE 1978).

Subsidence due to cavern roof collapse could affect the surface environment as well as surface facilities, buildings, equipment, and piping. Subsidence caused by salt creep and cavern closure is generally limited and slow. In shallow caverns, for example, subsidence rates of 0.5 mm per year are common (Wassmann 1993). However, Wassmann has reported several contributing factors to surface subsidence above salt caverns. For example, one particular salt cavern in the Hegelo brine field in the Netherlands subsided due to both overmining (1,100-mm subsidence in 1 year) and disintegration of the cavern roof, which was further weakened by geologic faulting. Eventually, the brine penetrated the roof, causing it to cave in slowly and steadily and ultimately creating a 35-meter crater within a couple of hours (Wassmann 1993).

It is important to note that in a disposal cavern the oil field waste will be in the form of a solid or semi-solid. Even if the roof of a disposal cavern should collapse, the solid or semi-solid wastes will not be displaced from the cavern to the extent that the fluids considered in the DOE collapse model would be. Therefore, the consequences of a roof collapse in a disposal cavern, in the event it should occur, would be less damaging than a roof collapse in a fluid-filled cavern.

Cavern Integrity - Although caverns can and should be designed to minimize the chance for collapse and subsidence, the use of caverns historically developed for other purposes and used today for disposal of oil field wastes must be carefully assessed. Although permitted at their time of development for hydrocarbon storage or brine production, their use specifically for disposal should consider location, size and shape, and proximity to nearby caverns and other activities that could in any way be affected in the longer term.

Location of cavern - A major factor in determining cavern stability is cavern depth. Deep cavities subjected to large overburden stresses are more likely to suffer excessive closure because the potential for large shear stress is greater than for shallow cavities (Coates et al. 1983). Nearness to salt formation boundaries and to other caverns within the salt formation also affects cavern stability — caverns near salt formation boundaries may induce high deviatoric stresses in more brittle rock outside the salt.

Cavern size and shape - Cavern size and shape affect in-situ stress changes, which in turn influence stress concentrations around the cavern. Short, wide caverns tend to produce larger stresses than high, narrow cavities of equal volume. Thus, for caverns of equal volume, those with relatively high height-to-diameter ratios are considered to be less subject to roof collapse than those with lower ratios.

Proximity to other caverns - When multiple cavities are created in salt domes, a primary consideration is the thickness of the walls between cavities required to maintain system stability. This design consideration is similar to that involved in designing supporting pillars for room and pillar mining and is two-fold. First, the initial design or spacing of multiple caverns must be such that the roofs will be adequately supported. Second, there is a potential for cavern diameter to increase. This increase could occur if there were unsaturated water in the wastes that could dissolve salt from the surrounding walls, thereby increasing the size of the existing caverns and further reducing the thickness of the salt wall between them. This process could be accelerated if seams of salt more soluble than sodium chloride were present in the formation. This concern can generally be addressed by basing the original cavern design on the anticipated increase in cavern diameter caused by additional leaching. Communication between caverns, or the passage of material through porous and permeable connections from one cavern to another, may also result from activities outside the cavern and outside the control of the cavern operator, especially when the disposal cavern is near other caverns that could expand.

By using comprehensive geotechnical computations, Wallner and van Vliet (1993) assessed changes in cavity stability and surface subsidence expected to result from enlarging several brine caverns in a salt dome in the Netherlands. Salt field operators planned to enlarge cavity diameters from 100 to 200 meters, leading to an increased volume and an increased ratio of cavity spacing-to-diameter approaching 2:1. The model indicated that the existing formation is stable because of a bridging effect – the inner region of the cavity array relaxes and the outer region of the dome receives the transferred stresses. The model also indicated that for this particular array, the stability of the cavities and the pillars would not be endangered by enlarging the cavity diameter, although the enlarged diameters resulted in slightly increased surface subsidence. The model predicted continued stability as the spacing-to-diameter ratio approached 2:1, although several published standards or regulatory requirements for hydrocarbon storage caverns require a spacing-to-diameter ratio of no less than 2:1 (CSA 1993; TNRCC 1995). The CSA standards allow alternate spacing if geological studies show that caverns may be closer. Another recent reference recommends a spacing-to-diameter ratio of 4:1 for hydrocarbon storage caverns unless site-specific geomechanical studies show that caverns may be closer (IOGCC 1995).

The Netherlands study also assumed that the cavities were open and subject to hydrostatic brine pressure only. The study suggested that long-term subsidence forecasts will depend on cavity abandonment and sealing criteria, which need to be developed and tested, and which "need substantial research effort and study in the years to come" (Wallner and van Vliet 1993).

Leakage of Cavern Contents - Although salt is by nature a creeping material and will theoretically seal under normal conditions, leaks from caverns have been encountered. DOE's SPR found one cavern at Sulphur Mines, Louisiana, that when tested, leaked at a rate of several hundred barrels per year. Other operations have occasionally experienced similar leaks. Such leaks are normally attributed to poor or deteriorated cement jobs on the entry well to the caverns. In the Sulphur Mines case, sacrificial nitrogen was maintained on the cavern roof during crude oil storage to preclude product loss. Additionally there has been at least one case in southern Louisiana of a cavern being accidentally leached through at the edge of the dome. It is important to note, however, that the vast majority of the hundreds of storage caverns in use have served as secure storage chambers and have not leaked.

Solubility of salt - All materials found in salt formations do not dissolve at the same rate. Certain nonsalt constituents (e.g., anhydrite) may dissolve at slower rates than sodium chloride, thereby leaving ledges, while other types of salts may dissolve more quickly than sodium chloride, creating unanticipated channels or enlarged areas within a cavern.

Type of salt formation - The type of formation in which the salt cavern is located may affect the potential for leakage. There are two general types of salt formations: bedded and domal, and there are significant variations in salt properties and characteristics within these two categories as well as within individual beds or domes. Bedded salt, which has historically been used for brine mining in west Texas, is often characterized by insoluble shale and anhydrite zones that jut into the cavern (see Figure 7). A concern has been raised that salt may be interbedded with porous or fractured rock layers, and that liquid waste might migrate out of the cavern through these layers, if such layers are present. However, this mechanism of migration is considered highly unlikely, because these layers would be expected to be plugged with salt. Mechanical integrity testing of disposal caverns would determine whether fluid migration through these layers is occurring.

Generally, salt domes contain salt that is relatively free of shale and anhydrite layers. The relative purity of the salt in the deeper domal areas allows uniform dissolution and the formation of regular caverns, although domal salt can also vary from formation to formation, and even within a formation. Physical tests conducted for the Solution Mining Research Institute to determine hydrofrac gradients (pressure gradients that will cause formations to physically fracture) of Gulf Coast salt domes showed that in-situ fracturing characteristics and containment properties of salt can vary greatly. The results also demonstrate that the hydraulic fracture gradient typically assumed for Gulf Coast domes leads to conservative practices in solution mining and storage (Thoms and Gehle 1990).

Construction and operating practices - During construction of a salt cavern for waste disposal, it will be necessary to avoid any serious damage (fracture, rupture) that might compromise cavern stability and long-term capacity for containment. Operating conditions and practices can lead to leakage if the integrity of the final cemented casing or the casing seat (a cemented base placed at the bottom of the casing) is compromised. Factors affecting the pressure of the casing seat include disposal injection rate, casing and tubular configuration, and system back pressure. A specific example of how system piping, wellheads, and the cavern formation can be damaged is through excessive pressure surges caused by the sudden stoppage of a flowing stream. This can happen if (in the case of hydrocarbon storage wells) product is injected or withdrawn at very high flow rates (API 1993). API reports that brine, fresh water, and some relatively non-compressible materials can cause pressure shock waves severe enough to damage piping, wellheads, and the cavern formation. Thus, it is possible that injection of oil field wastes at pressures that are too high could lead to sudden stoppages, or "water hammer" effects. The disposal caverns permitted in Texas operate at much lower injection pressures than most hydrocarbon storage caverns. Consequently, water hammer effects should not be a problem.

Approaches for Mitigating Potential Failure Modes

The concerns raised above can be addressed through appropriate design, construction, operating, and closure procedures. Presented below are suggestions for mitigating potential adverse consequences associated with using salt domes for disposing oil field waste.

Computer Modeling - Many of the concerns described above can be predicted with computer programs that forecast closure and subsidence rates. Cavern design and operating procedures can then be modified, if necessary, on the basis of the results. However, because each situation is different, such programs must be calibrated to the special circumstances of each location and not all phenomena can be modeled accurately. Thus, while modeling is valuable for helping to mitigate potential adverse effects, empirical data and actual measurements are also useful.

Site Selection Criteria - Several factors should be considered in selecting sites for disposal of oil field wastes. These include many suggested by the Interstate Oil and Gas Compact Commission for siting natural gas storage caverns (IOGCC 1995):

- Distance to populated areas;
- Proximity to other industrial facilities;
- Current and future use of adjacent properties, including agriculture, which may withdraw large amounts of groundwater and potentially increase subsidence rates;
- Handling of brine or other displaced fluid;
- Proximity to environmentally sensitive wetlands, waters, and fresh water aquifers;
- Proximity to the salt boundary; and
- Proximity to other existing and abandoned subsurface activities, e.g., neighboring caverns for brine, gas, or hydrocarbons.

Another consideration for siting is the potential for seismic activity.

Design Considerations - To minimize the chance for failure due to closure, collapse, or leakage, acceptable designs should be based on a geological review of the location that covers all features capable of affecting the cavern. Adequate studies should address regional stresses and strains; mechanical, chemical, and containment properties of the salt and confining rock formations; and structural anomalies, including faulting (IOGCC 1995). The design should also consider potentially associated low-permeability zones and the effects of those zones on disposal operations (CSA 1993). Detailed knowledge of the geology should be supported by adequate documentation. Operators should be able to demonstrate that the caverns they plan to use — either new caverns developed specifically for oil field waste disposal or existing caverns that are being converted — will remain stable in the future.

Construction Considerations - Following cavern construction and before waste disposal begins, inspection and testing should be conducted to verify the tightness of the cavern, and to ensure that there is no hydraulic communication between the cavern and other caverns or elsewhere outside the salt formation.

Operating Considerations - During disposal operations, records of operation as well as measurements of subsidence and cavern integrity should be made periodically. Care must be taken to ensure against conditions that would cause the pressure at the cemented casing seat to exceed the fracture pressure. Emergency planning should also be undertaken to address accidental releases of brine or oily substances.

Chapter 6 - Disposal Operations

The Disposal Process

Initially, caverns are filled with clean brine. Wastes are introduced as a slurry of waste and a carrier fluid (brine or fresh water). A carrier fluid that is not fully saturated with salt will eventually leach salt from the cavern walls or roof. Expansion of cavern diameter is generally not a problem as long as the anticipated degree of expansion is accounted for when designing the caverns. To avoid excessive leaching of the cavern roof, operators may intentionally introduce a hydrocarbon pad that, by virtue of its lower density, will float to the top of the cavern and keep the unsaturated carrier fluid from coming in contact with the cavern roof.

As the waste slurry is injected, the cavern acts as a oil/water/solids separator. The heavier solids fall to the bottom of the cavern, forming a pile. Any free oils or hydrocarbons that are associated with the waste float to the top of the cavern. Clean brine displaced by the incoming slurry is removed from the cavern and either sold as a product or disposed of in an injection well. When the cavern is filled, the operator removes the hydrocarbon pad and plugs the cavern. The remainder of this chapter provides greater detail on the disposal process and discusses issues relating to disposal.

Carrier Fluid Considerations

Fully saturated brine is a good carrier fluid, but it may not always be available or may be too costly. Using fresh water or brines that are not fully saturated as carrier fluids does not present major difficulties, however. Under this scenario, the operator would need to be aware of the effect the carrier fluids would have on additional salt leaching. Although the presence of fresh water should cause only a relatively small change in the diameter or height through leaching, under certain circumstances, the amount of additional leaching could reduce the intra-cavern distance, the distance to the edge of the salt formation, or the cavern roof thickness to a degree that would be considered undesirable. Therefore, if the waste contains fresh water or less than fully saturated brine, the operator and the regulatory agency would need to agree in advance on the extent of additional leaching that would be allowed at that particular site and how that leaching rate could be controlled.

While caverns will expand if carrier fluids are not fully saturated, the extent of expansion is generally not particularly large. For example, if a cavern is filled completely with fresh water, which subsequently dissolves enough salt to become fully saturated, the cavern volume is expected to increase by only one-sixth and the diameter is expected to increase by only 8 percent (Diamond 1996).

Waste Emplacement Considerations

There are three potential ways to fill the cavern:

1. The waste can be pumped down the tubing and the displaced brine withdrawn from the annulus;

2. The waste can be pumped down the annulus and the displaced brine can be withdrawn from the tubing; and

3. The waste can be pumped down one well and the displaced brine can be withdrawn through a second well.

The first scenario described above is the one most likely to be used. The heavier solids in the incoming waste will be introduced near the bottom of the cavern and will have a good chance of settling and remaining in the cavern. Some of the hydrocarbons rising through the cavern may become entrained in the displaced brine that is leaving the cavern, although most hydrocarbons will accumulate in a pad or layer near the roof.

One operator in Texas follows the second scenario. Waste is introduced near the top of the cavern. The lighter material will remain at the top of the cavern while the heavier solids must fall through many feet of brine before reaching the cavern bottom. The heavier solids are moving in the same direction as the displaced brine and may mix with the displaced brine and be carried out of the cavern.

Another Texas disposal cavern operator started disposal operations with a single well and injected waste through the tubing. The cross-sectional area of the tubing and the annulus limited the rate at which the cavern could be filled. To provide additional cross-sectional area to enhance the rate of filling, the operator recently drilled a second well and is now operating the cavern using one well for injection and the other well for brine withdrawal.

Injection at the bottom of the cavern presents the problem of changing the injection tubing depth as the cavern fills. Operators of oil field waste disposal caverns using injection through the tubing inject waste until the end of the tubing is covered or the back pressure from the accumulated waste precludes further injection. At this point, the operators use a small controlled explosive charge to cut off the end of the tubing further up the cavern and then can resume filling the cavern.

Displaced Fluids Considerations

As the solid components of the incoming waste fill the bottom of the cavern, an interface forms between the accumulated waste and the overlying brine, including a transition zone of brine that is mixed with the waste. Early in the life of a disposal cavern, brine is withdrawn hundreds of feet above the surface of the waste pile or the transition zone. The vast majority of the displaced brine will be clean. As the cavern fills, however, the transition zone brine may make up a larger proportion of the remaining cavern volume. At some later time, the brine withdrawn from the cavern will consist partially or completely of brine from the transition zone. The transition zone brine will be noticeably dirtier than the clean brine that was originally displaced from the cavern. The waste/brine interaction in the transition zone should have no effect on the nonhazardous classification of the brine or on the environmental suitability of cavern disposal. However, there may be unanticipated operational concerns and expenses.

Displaced brine is generally sold as a product or injected into brine disposal wells. As long as the brine is clean, either method of managing displaced brine can be practiced without additional treatment or handling. However, as the transition zone brine is displaced from the cavern, the operator may be faced with additional expense to clean up the brine before it can be injected underground for disposal. Solids-laden brine could clog the formation into which it was injected; typically such wastes are filtered prior to injection. Since most of the brine that is sold is used as a constituent of drilling fluids to drill additional oil and gas wells, the presence of waste components in the brine may not affect its salability.

An alternative to cleaning up the displaced fluid for disposal is early abandonment of the cavern, before it is completely full. This results in less disposal volume than was initially planned, with a resultant loss in revenue. Yet another alternative is to fill a cavern until the displaced brine shows characteristics of the transition zone. At that point the operator could discontinue disposal for a period of time, allowing the solid wastes to more completely settle and minimizing the extent of the transition zone.

Displaced brine that is sold should not contain excessive levels of contaminants. Regulatory criteria for acceptable levels of contaminants or on the projected end use may be appropriate.

Other Considerations

Monitoring of cavern pressure should be done before the cavern is filled with oil field waste, throughout the waste emplacement cycle, and optimally, for some period of time after the cavern has been closed. In order to monitor cavern pressure after closure, a pressure transducer must be installed in the cavern at the time it is closed.

The types and volumes of wastes emplaced should be recorded on a regular basis and the records should be maintained for several years following closure of the cavern.

Since there is very limited experience with operating salt caverns for disposal of oil field waste, certain facets of operation could benefit from additional research. The few oil field waste disposal caverns in operation have not yet become full. There will be differences in brine quality as the caverns fill. Research could provide information useful to operators on how to control brine quality and when brine will have to be treated prior to disposal or sale.

Chapter 7 - Closure and Remediation

Although various industries have been operating storage and production caverns for years, the long-term behavior of caverns filled with oil field waste is unknown. Scientists have modeled cavern behavior and engineers have conducted limited tests of closed brine-filled caverns. Most have studied liquid-filled salt caverns, although some have modeled hazardous waste disposal in dry caverns. The extent to which preliminary findings in these areas relate to the behavior of caverns used for oil-field wastes is not known. However, it will depend at least in part on the ratio of brine (or other liquid waste contents) to solids and on the densities of the solid wastes relative to those of the surrounding salt. To present the current thinking regarding closure and abandonment and to highlight some of the issues associated with such activities, the status of knowledge related to closing and abandoning caverns is addressed in this chapter.

Concerns with Sealing and Abandoning Caverns

Sealing and Abandonment of Liquid-Filled Caverns

The general concern with sealing and abandoning a fluid-filled salt cavern is that the continued creep of the cavern can raise the fluid pressure at the top of the cavern to a value greater than that of the lithostatic pressure at that point (Bishop 1986). This condition can lead to a possible fracture in the area of the wellbore, allowing brine to be forced out of the cavern.

The SPR has only cursorily addressed the abandonment of SPR caverns. Saline aquifers or impermeable caprock overlay the salt around the SPR salt domes. When the SPR caverns are closed, they will be sealed as state law requires. However, even state concerns relative to brine escaping into saturated aquifers or caprock are minimal for SPR caverns. Other sites for existing or potential waste disposal caverns may be located in areas that pose greater risks. Each site should be individually evaluated for its risk potential.

In 1984, the Solution Mining Research Institute sponsored a study using computer simulations combined with knowledge of the material properties of rock salt and with comparisons with actual pressure buildup data obtained in field operations to analyze the long-term behavior of a solution cavern sealed with a cement plug (Serata 1984a). While the simulations showed the plugged cavern to steadily approach structural equilibrium with permanent stability, they also disclosed a potential danger resulting from cavern pressure buildup. If the cavern pressure buildup were to exceed the surrounding ground pressure at the cavern top or at the wellbore below the cement plug, the excess pressure could lead to brittle fracture or plastic yield, depending on the strength of materials and initial stress states at the elevation of the cement plug. Factors contributing to the magnitude of cavern pressure buildup include bottom depth, thickness and size of salt mass behind the cavern wall, proximity to cavern boundaries, influence of neighboring caverns, cavern geometry, and the initial stress state at the cavern bottom (Serata 1984b).

Serata (1984a) hypothesizes a critical depth of 1,000 feet. If the cavern top is higher than the critical depth, then the cavern roof may crack and leak. Likewise, if the wellbore plug is set above the critical depth, the wellbore would be fractured, creating a direct conduit for cavern contents to reach the surface. However, more recent research suggests that this hypothesis cannot be supported (Linn 1995).

Bishop (1994) calculates that the salt strength of domes and the compressive strength of the cement plug in the wellbore is typically much greater than the lithostatic pressure. Consequently, Bishop believes that fracturing is unlikely.

In 1994, anticipating eventual sealing and abandonment of SPR caverns, DOE sponsored a series of modeling efforts to gain insight into the long-term behavior of a typical SPR cavern (Ehgartner and Linn 1994). To predict the speed and extent of cavern pressurization, the individual and combined effects of salt creep, salt dissolution, and geothermal heating of brine on the pressures generated after plugging were modeled. The models showed that after plugging, the internal fluid pressures in a brine-filled cavern eventually exceed lithostatic pressure in the upper portion of the cavern, resulting in enlargement and increased potential for leakage. The time needed for the brine pressure to exceed the lithostatic pressure varies with brine temperature and salinity. Assuming no salt dissolution after plugging the cavern, the predicted time for geothermally heated brine to reach lithostatic pressure at the casing seat was only about two years; without geothermal heating of the brine, the predicted time was over 200 years. Salt dissolution had the effect of nearly doubling the time needed to reach lithostatic pressure. The authors suggested that the sensitivity of cavern brine pressures to temperature and salt dissolution can be used to increase the time before the casing seat exceeds lithostatic pressure and decrease the maximum fluid pressure exerted on the casing seat. Thus, heating the brine and using brine of lower salinities could help decrease fluid pressure on the casing seat. The authors conclude, however, that even without heating the brine or delaying installation of the plug, the predicted rate of brine pressurization is not high enough to result in fracturing of the salt.

A more recent study of the behavior of sealed solution-mined caverns suggests that the factors affecting cavern closure include not only brine heating and cavern creep, but also rock salt permeability. More importantly, rock salt permeability, even if very small, allows some pressure release and leads to a final equilibrium pressure that can be substantially lower than the lithostatic pressure (Berest and Brouard 1995). The authors reported three test cases. The first concerned shallow brine production caverns in France and showed that during the test measurement period, the predominant effect was thermal expansion (neither percolation nor creep played major roles). The second case was a cavern operated by Gaz de France that was closed roughly one year after leaching had ended and was kept closed for about 7½ months. Tests showed that thermal expansion remained active and could be considered responsible for 80 to 90 percent of the observed brine outflow. The third test was conducted in much deeper caverns (rock salt layers between 1,800 meters and 2,500 meters) and showed that for deep caverns, cavern creep is much more important than thermal expansion. However, when the gap between lithostatic pressure and brine pressure becomes very small, creep is ineffective and thermal expansion becomes the primary contributor to pressure buildup.

Berest and Brouard (1995) found that pressure buildup generated by salt creep and brine heating in a sealed cavern leads to a final equilibrium pressure that is smaller than lithostatic pressure, provided that surrounding rock salt exhibits some permeability. They suggest that cavern operators consider such permeability in order to evaluate the area, especially prior to leaching. However, they acknowledge that salt permeability may not be sufficient to avoid a transient period in which the pressure in the cavern exceeds the lithostatic pressure. They suggest that this problem can be mitigated by injecting nitrogen or air into the cavern prior to plugging to modify cavern compressibility and reduce pressure buildup rate and also by delaying plug installation until the salt has heated the brine.

The temperature differential between the bottom and top of a tall cavern can lead to convective mixing of the fluids in the cavern. For oil field waste disposal caverns, the convection is unlikely to disturb the solid or semi-solid waste layer at the bottom of the cavern, but it could mix the overlying brine. This is not anticipated to lead to cavern failure[9].

The current literature cited above, whose conclusions are based on modeling, suggests that brine-filled caverns will not leak. However, no empirical tests of these suggestions have been reported in the literature to date.

Sealing and Abandonment of Waste-Filled Caverns

It is not known how these findings for brine-filled caverns will translate to caverns filled with oil field waste. Presumably there will be some brine remaining in a waste disposal cavern at the time of closure, because the likelihood of the displaced brine coming from the transition zone increases as the amount of waste disposed increases. Therefore, the disposal process will likely reach a point at which the displaced brine can no longer be economically extracted and treated or disposed of. Further, there will be brine or other fluids in the pore spaces surrounding the solid waste particles and the rubble at the bottom of the cavern deposited during cavern formation. The wastes near the bottom of the cavern may contain less pore fluids because the increased pressure at that depth will have packed the particles more tightly. Although the solids portion of the waste mass will resist salt creep, the brine portion is likely to be subjected to creep and geothermal heating.

[9] Personal communication between David Tomasko, Argonne National Laboratory, Argonne, IL, and John Veil, Argonne National Laboratory, Washington, DC, on January 24, 1996.

The effect of geothermal heating may not be as significant for waste-filled caverns as for fluid-filled caverns because the anticipated filling rate is slower than for fluid-filled caverns.

The oil field wastes will have a longer time to reach formation temperatures before the cavern is sealed.

Because no caverns filled with solid waste have been sealed, most of the information on the behavior of sealed, solid-waste-filled caverns is based on modeling and theory. The two studies cited below both consider disposal of predominantly dry wastes into dry caverns. It is not known how their conclusions relate to the scenario of disposing of a slurried solid/semi-solid waste into a fluid-filled cavern.

One preliminary study (Tinucci et al. 1988) modeled the response of a hazardous waste-disposal cavern in three stages over a 200-year modeling period. The stages consisted of a 5-year period for cavern creation through solution mining, a 2-year waste emplacement period (in the first 2 years the cavern was assumed to be empty, then filling occurred at the end of the 2-year period), and a 193-year sealed period. The waste material was assumed to be a weak compressible solid of high porosity in a pelletized form with low shear strength. The modeling results indicated that most deformation occurred when the cavern was empty, with a cavern volume reduction of 1.1 percent in the first 7 years, and less than 0.2 percent thereafter. However, depending on the creep equations, the results could be 3 to 5 times higher. Upon sealing, the model predicted rapid pressure buildup within 6 months, and then a levelling off. While the pressure at the top of the cavern did not significantly exceed the original lithostatic pressure, the cavern pressure was expected to exceed lithostatic pressure eventually if the stresses came to equilibrium and the cavern did not leak off pressure. Modeled deformations were large enough to fracture several of the zones, but fracturing diminished over time.

Crotogino (1990), while studying disposal of hazardous wastes into dry, empty caverns, identified at least two particular concerns for closure of caverns filled with solid wastes. The first relates to the possibility of fluid-like pressure buildup. To avoid this, the mechanical properties of the waste should be such that shear stress will be absorbed. The other concern is the possible subsidence of the surface due to the porosity of the waste materials. Upon introduction, waste materials have a porosity of 30 to 40 percent, a factor which is subsequently reduced by the impinging rock pressure. To predict cavity convergence, lab tests can be used to project compaction behavior. The objective is to achieve elastoplastic behavior of the waste by undertaking corresponding conditioning.

Approaches for Addressing Concerns

Because neither the behavior nor the impacts of a breach of cavern integrity after closure are well understood, it is difficult to suggest mitigating approaches. It can be argued that because of the unknown factors, the approaches should be conservative. However, if the impacts of actual breach of containment are low (as would be the case for caverns located away from aquifers and human activity), then it could be argued that the regulatory approach should not entail overly prescriptive and conservative requirements. Argonne National Laboratory has received funding from DOE to conduct a preliminary risk and cost analysis of salt caverns compared to other methods for disposing of oil field wastes during 1996. The findings of this study will contribute to a better understanding of the risks and impacts associated with cavern disposal.

The following issues should be considered when establishing regulatory requirements.

Testing and Analysis - Plugging and abandonment requirements should incorporate such tests as

- Geomechanical analyses of stability of the cavern and its roof prior to abandonment; and
- Pressure tests to ensure integrity of the cavern, wellbore, and cement prior to setting plugs or to demonstrate that the waste will remain in the cavern.

Plug Design - The standards developed for plugging hydrocarbon storage caverns are applicable for disposal caverns too. For example, the IOGCC (1995) standards call for installation of a drillable bridge plug within 30 feet of the casing shoe (a reinforcing collar of steel attached to the bottom of the casing) or the end of the casing if no casing shoe is present. The bridge plug is then capped with a plug of salt-saturated, sulfate-resistant cement to a depth sufficient to cover two casing collars. Additional plugs should be located within the wellbore to cover all porous or permeable zones between the casing shoe and the surface.

Some of the research into hazardous waste disposal has considered alternative plugging designs and materials. Crotogino (1990) suggests that both long-term and short-term sealing needs must be met. Long-term sealing requires a material that compacts under the effects of pressure, temperature, and humidity. Crushed rock salt appears to meet those requirements and should be considered as a component of the borehole plug. Over time, it recrystallizes to a homogeneous material that is barely distinguishable from naturally occurring rock salt, and it can be introduced as a bulk material, which gradually joins with the surrounding rock over the long term. However, since salt fines do not produce a fully functioning seal in the intermediate term, it may be necessary to seal part of the uncased section with low-permeability grout plugs (e.g., salt concrete or bitumen). Research regarding the use of plugs of designed viscosity to achieve a permanent seal is under way. A plug should have a viscosity high enough to act as a pressure seal and low enough to allow existing pressures to force it against the salt, enhancing the ability of the highly viscous salt to conform exactly to the perimeter of the plug (Bishop 1986).

Pressure Relief - One approach to relieving pressure created by cavern closure after sealing would be to bleed off brine as necessary. Under this approach, operators would need to demonstrate that there was sufficient brine remaining in the cavern after closure to allow bleeding and would have to maintain monitoring and responsibility for several years following cavern closure.

Summary Opinions of Independent Experts

To better assess the significance of these reports and findings, the authors interviewed several experienced researchers in the field to learn their opinions. Dr. James Linn of Sandia National Laboratories suggests that for liquid-filled caverns, researchers don't know what will happen, although if cavern pressure buildup is slow, the caverns should not fail. Dr. Linn also suggests that solids-filled caverns will not transmit pressure like fluid-filled caverns and consequently will not fail. Caverns filled with noncompressible solids with porosity are more stable than caverns filled with brine, but lighter, more compressible solids provide less stability than noncompressible solids. The relative stability depends on the nature of the waste[10].

Dr. Joe Ratigan of RE/SPEC Inc. suggests that researchers have a good knowledge of fluid-filled cavern behavior up to internal pressures of 0.8-0.9 times lithostatic pressure, but they disagree as to what will occur beyond that point. The potential weak links where fractures could occur include the casing plug, the cement filling the annulus, and the rock itself. Another avenue for waste leakage from the cavern would be for the cavern contents to diffuse into the rock mass[11].

Dr. Robert Thoms of AGM Inc. suggests that very tall liquid-filled caverns could experience leakage problems at the top due to increased pressure following closure, but caverns that are shorter would be less likely to leak. Caverns filled with solids that have sufficient shear strength and adequate void spaces should have little chance of leakage. The weight of the waste pile will exert lateral pressure on the cavern walls and provide additional stability. Dr. Thoms suggests that one additional safeguard that could be employed is to fill the cavern, monitor pressure for several years, and then permanently seal the cavern[12].

As part of the Solution Mining Research Institute's comments on the second draft of this report (Diamond 1996, comment 96), two persons experienced in the salt cavern industry added

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[10] Personal communication between James Linn, Sandia National Laboratories, Albuquerque, NM, and John Veil, Argonne National Laboratory, Washington, DC, on December 8, 1995 and May 14, 1996.

[11] Personal communication between Joe L. Ratigan, RE/SPEC Inc., Rapid City, SD, and John Veil, Argonne National Laboratory, Washington, DC, on December 7, 1995 and May 14, 1996.

[12] Personal communication between Robert L. Thoms, AGM Inc., College Station, TX, and John Veil, Argonne National Laboratory, Washington, DC, on December 11, 1995.

additional insights on the stability of caverns filled with solids versus caverns filled with brine. Fritz Crotogino of Kavernen Bau- und Betriebs GmbH commented that his research found that solids can have a porosity exceeding 40 percent and that significant cavern pressure reduction only occurs after compaction of over 20 percent (Crotogino 1990). Mr. Crotogino expects that slurried oil field wastes introduced to a brine-filled cavern will behave in the same manner as primarily dry solids introduced into a dry cavern, the situation on which he reported in Crotogino (1990). Mr. Crotogino suggests that compaction of 20 percent can only be expected after a long period of time at the internal pressure corresponding to a brine column and as long as the waste material has not been compacted to a considerable extent, there will be no increase in internal pressure.

The second person who expressed an opinion on this issue is Charles Chabannes of Sofregaz US Inc. Mr. Chabannes suggests that solid particles in the waste pile will probably not offer structural support until nearly all the pore space has been eliminated by creep-induced compaction (Diamond 1996, comment 96).

Although the comments from Mr. Crotogino and Mr. Chabannes may appear to disagree with the statements attributed to the other experienced researchers, Dr. Thoms suggests that different experts have focused on different aspects of the fill material issue and that all of their comments are valid. He offers the following summary (Thoms 1996). As a general rule, the stability of liquid-filled caverns increases with the density of the filling liquid. Caverns that are filled by displacing brine with materials more dense than brine will be more stable than those filled with brine alone. As solid particles are injected into a cavern, they introduce additional lateral forces that reinforce the stabilizing effect of the brine pressure acting outward against the cavern walls. The lateral forces have two components. The first component is lateral confinement of the solid particles by the cavern walls, which is influenced by the weight and interlocking characteristics of the solids. The second component is a propping resistance of the solids matrix in response to inward creep of the cavern walls; it tends to increase over time. If the waste pile contains large void spaces (e.g., Crotogino's 40 percent porosity), significant wall movements may be necessary to incur any propping effects.

Dr. Thoms indicates that Mr. Crotogino's and Mr. Chabannes' comments are consistent with the concept that a brine cavern that exhibits little salt creep before waste introduction will initially gain little additional stability from the propping resistance of a solid waste pile with considerable porosity. However, the presence of the solids in the cavern represents a measure of insurance against long-term creep effects. If the nature of the incoming waste is such that it deforms readily, as would a brine/oil field waste slurry, there will be an immediate gain due to confinement effects. In summary, disposal of solids into brine-filled caverns will generally tend to enhance the stability of caverns. The degree of stability enhancement depends on the nature of the material (Thoms 1996).

The experts are in agreement that disposal caverns are likely to be stable, if designed and operated properly. Even if waste-filled caverns are no more stable than brine-filled caverns, they still are very stable, as indicated by literature studies. If waste-filled caverns prove to be more stable than brine-filled caverns, either initially or at a later point following creep-induced compaction, the additional margin of safety further reduces the likelihood of cavern leakage.

Remediation Considerations

There appears to be undue concern about escape of waste from a cavern if its structural integrity is breached. Most oil field wastes that would be placed in a cavern for disposal are solids or semi-solids and would not move an appreciable distance even if the cavern ruptured. All that remains to cause concern is oil and brine. The movement of oil would be limited if it were not accompanied by water. It would tend to adsorb on rock or soil and its movement would be minimized. The most significant danger from a waste disposal cavern failure is the escape of brine. If a failure occurred that allowed brine to escape, it would pose the greatest threat if it reached formations containing fresh water.

If brine were to escape from the cavern, the proper remediation would consist of recovery wells that could capture the escaped brine before it reached fresh water formations, assuming that the leak was detected before fresh water contamination occurred. If a drinking water aquifer becomes contaminated with brine, there are a variety of techniques that can be used for remediating the aquifer. Most state groundwater protection or waste site cleanup agencies have extensive experience with these techniques.

Matalucci (1993) provides a thorough review of techniques that could be used to repair leaks in the SPR caverns. The same techniques are applicable to the borehole and casings of disposal caverns too. The techniques reviewed by Matalucci include

- Inner full-length cemented liner;
- Inner uncemented liner options using external casing packers;
- Internal steel liner casing patch (HOMCO patch); and
- Various squeeze cementing options using small-particle-size cementing materials.

It would seem more prudent to design for low risk than to have to counteract failure. A viscous waste containing little brine, that kept all its constituents in a contiguous mass and that filled the cavern completely before closure would appear to pose the least risk.

Areas for Further Research

The current state of knowledge about the long-term behavior of closed waste-filled caverns is incomplete. Research in several key areas would improve our understanding of what happens in closed caverns and the risks that closed caverns pose relative to other disposal mechanisms. These areas include

- Defining ways to conduct long-term monitoring of closed caverns (particularly caverns filled with oil field wastes) to ensure that leaks are discovered in a timely manner, including defining parameters to be monitored and how the monitoring would be done;
- Identifying and evaluating the risks associated with waste disposal cavern behavior following closure and the impacts of a containment breach should it occur;
- Estimating the relative risk of disposing of oil field wastes in salt caverns compared to other existing disposal methods; and
- Identifying and assessing the costs and benefits of various methods for disposing of oil field wastes.

Chapter 8 - Conclusions

This report presents an initial evaluation of the suitability, feasibility, and legality of using salt caverns for disposal of nonhazardous oil field wastes. Given the preliminary and general nature of this report, we recognize that some of our findings and conclusions may be speculative and subject to change upon further research on this topic.

- This particular mode of disposal is in its infancy. At the time this report was prepared, we could identify only six U.S. facilities permitted for this type of disposal, and only four of those were in an active status as of May 1996. While there appears to be interest from several oil-producing states in considering this method of oil field waste disposal, no other state has approved any project yet and only New Mexico has received an application for siting and operating a disposal cavern.

- There are no apparent regulatory barriers to the use of salt caverns for disposal of oil field wastes at either the federal level or in the eleven states discussed in this analysis. One area that would benefit from clarification is further EPA guidance on what types of wastes may be disposed of into Class II wells.

- The types of oil field wastes that are exempted from RCRA hazardous wastes requirements are generally suitable for disposal in salt caverns. Many of these wastes are now disposed of in landfills or are land-farmed; these disposal methods pose environmental risks of their own.

- There are many variables to consider when siting, constructing, and operating a waste disposal cavern. The hydrocarbon storage industry has developed useful, detailed standards, guidance, and criteria for designing and constructing caverns; these are appropriate for waste disposal caverns, too. Hundreds of storage caverns have successfully been operated worldwide for several decades.

- There is no actual field experience on the long-term impacts that might arise from salt cavern storage of oil field wastes. The literature contains many theoretical studies that estimate what might happen following closure of a cavern. Although different authors agree that pressures will build in a closed cavern due to salt creep and geothermal heating, they do not specifically address caverns filled with oil field wastes. Several experienced researchers in the field interviewed by the authors believed that caverns filled with oil field wastes presented much less likelihood of leakage than fluid-filled caverns, although other experienced researchers believed that until the pore space of the waste pile is reduced through creep-induced compaction, a solids-filled cavern will behave in the same way as a fluid-filled cavern. More field research on the effects of pressure buildup in closed caverns would aid our understanding of this subject.

- No attempt was made in this study to evaluate the cost effectiveness of cavern disposal of oil field wastes. Additional research in the areas of risk assessment and costs of cavern disposal compared to other alternatives for oil field waste disposal, some of which will be conducted by Argonne National Laboratory during 1996, will facilitate the development of efficient and effective policy.

- On the basis of this preliminary research, we believe that disposal of oil field wastes into salt caverns is feasible and legal. If caverns are well-sited and designed, operated carefully, closed properly, and monitored routinely, they represent a suitable means of disposing of oil field wastes.

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Table 1 - State Activities Regarding Disposal of Oil Field Waste into Salt Caverns (continued)

State	Contact	Are salt caverns being used in your state for disposal of oil industry waste?	Has this practice ever been considered?	Are there any state regulations specifically addressing disposal of oil field waste into salt caverns?	Comments
TX	Richard Ginn Texas Railroad Comm. Austin, TX 78711-2967 512/463-6796 or Jeb Boyt 512/463-7562	Yes Texas has four salt caverns that accept O&G production wastes.	N/A	Proposed regulations have been drafted.	The first facility was established four years ago. The wastes that are being disposed of in these caverns have a high solids content (suspended solids), which make them less suitable for typical Class II injection. The salt brine that is displaced from the cavern to make space for the O&G waste is disposed of in Class II wells.
LA	James Welsh LA Department of Natural Resources P.O. Box 94275 Baton Rouge, LA 70804 504/342-5515	No	Yes	No	No hazardous waste can be disposed of via injection wells in Louisiana. He indicated that injection of production waste streams with a high solids content (cuttings, drilling fluids, etc.) are not much of an issue with injection into Class II wells when the technology (ball mills or grinders) is used to grind the solids into fine particles. They are open to the idea.
MI	R. Thomas Segall MI Dept. of Natural Resources P.O. Box 30028 Lansing, MI 48909 517/334-6923 or Raymond Ellis 517/334-6923	No	Yes	No	Michigan is interested in knowing what the other states are considering. They currently permit cavern use for liquid natural gas storage.
OH	Dennis Crist OH DNR Fountain Square Columbus, OH 43224 614/265-6926	No	Yes	No	He thinks it is a good idea for the disposal of solid wastes (drilling fluids) not typically disposed of in Class II wells. He feels that a Federal Advisory Committee on the subject should be considered.
KS	Richard Hestermann KS Corp. Comm. Colorado Derby Bldg., Rm 200 Wichita, KS 67202 316/337-6200	No	No	No	He indicated that he was not aware of any discussions about permitting such activity in the state of Kansas. Some of the older solution mines that had been abandoned and injection wells that had gone through these salt deposits have been assumed responsible for sink holes that have occurred in Kansas. It is thought that fluid traveling down hole along the casing through the salt deposit displaced the salt and created a void that eventually collapsed.

Table 1 - State Activities Regarding Disposal of Oil Field Waste into Salt Caverns (continued)

State	Contact	Are salt caverns being used in your state for disposal of oil industry waste?	Has this practice ever been considered?	Are there any state regulations specifically addressing disposal of oil field waste into salt caverns?	Comments
OK	Bruce Langhus OK Corp. Comm. Jim Thorpe Building Oklahoma City, OK 73105 405/521-2500	No	No	No	The salt deposits in Oklahoma are not thick and conducive to solution mining. There is only one solution mine in the state.
MS	Fred Hille State O&G Board 500 Greymont Ave., Suite E Jackson, MS 39202 601/354-7127 or James Crawford Dept. of Env. Quality P.O. Box 10385 Jackson, MS 39289 601/961-5354	No	Yes	He indicated that the existing state regulations do not prohibit this practice. No state regulations would need to be changed to allow this practice.	They had been thinking that the disposal of Naturally Occurring Radioactive Material (NORM) wastes from O&G production might be effectively disposed of in salt caverns. Mississippi is very interested in what other states are thinking.
ND	Charles A. Koch ND Industrial Comm. 600 E. Boulevard Ave. Bismarck, ND 58505 701/328-5357 or Wesley Norton 701/328-2969	No	No	No	North Dakota only has one solution mine. It is in an O&G production area. Several years ago the state considered using salt caverns for storage but made the decision not to. O&G drillers have experienced many casing problems through the salt section which is approximately 600 feet thick. He did not feel that North Dakota would likely utilize salt caverns for O&G waste disposal since the salt formations are very deep.
NM	David Catanach NM Oil. Conserv. Div. P.O. Box 2088 Santa Fe, NM 87504 505/827-7131	No	Yes	No	NM Oil Conservation Division has received an application from a company interested in developing a commercial oil field waste disposal facility in NM. The NM Oil Conservation Division will be handling the application. The existing state regulations are silent on the subject.

Table 1 - State Activities Regarding Disposal of Oil Field Waste into Salt Caverns (continued)

State	Contact	Are salt caverns being used in your state for disposal of oil industry waste?	Has this practice ever been considered?	Are there any state regulations specifically addressing disposal of oil field waste into salt caverns?	Comments
NY	John C. Harmon NY Dept. of Env. Cons. 50 Wolf Road, Rm 202 Albany, NY 12233 518/457-9633 or Bradley Field 518/457-0100	No	No	No	Several years ago, there was some consideration of permitting disposal of municipal fly ash into a large conventional salt mine. However, a roof collapsed in a portion of the mine, causing flooding of the cavern, and the permit was never granted. He stated that injection of O&G waste into salt caverns is not likely in New York. There is little need for the disposal of solid drilling waste because most of the wells are air drilled (not utilizing drilling fluids).
PA	James Erb PA Dept. of Envir. Resources P.O. Box 2357 Harrisburg, PA 17120 717/772-2199	No	No	No (See Comments)	The Division of O&G has rules to permit the use of caverns for gas storage, but the Bureau of Labor and Industry regulates caverns. There are several storage caverns permitted.

Table 2 - Oil and Gas Wastes Exempted from RCRA Hazardous Waste Requirements (53 FR 25446, July 6, 1988)

- Produced water;
- Drilling fluids;
- Drill cuttings;
- Rigwash;
- Drilling fluids and cuttings from offshore operations disposed of onshore;
- Well completion, treatment, and stimulation fluids;
- Basic sediment and water and other tank bottoms from storage facilities that hold product and exempt waste;
- Accumulated materials, such as hydrocarbons, solids, sand, and emulsion from production separators, fluid treating vessels, and production impoundments;
- Pit sludges and contaminated bottoms from storage or disposal of exempt wastes;
- Workover wastes;
- Gas plant dehydration wastes, including glycol-based compounds, glycol filters, filter media, backwash, and molecular sieves;
- Gas plant sweetening wastes for sulfur removal, including amines, amine filters, amine filter media, backwash, precipitated amine sludge, iron sponge, and hydrogen sulfide scrubber liquid and sludge;
- Cooling tower blowdown;
- Spent filters, filter media, and backwash (assuming the filter itself is not hazardous and the residue in it is from an exempt waste stream;
- Packing fluids;
- Produced sand;

- Pipe scale, hydrocarbon solids, hydrates, and other deposits removed from piping and equipment prior to transportation;

- Hydrocarbon-bearing soil;

- Pigging wastes from gathering lines;

- Wastes from subsurface gas storage and retrieval;

- Constituents removed from produced water before it is injected or otherwise disposed of;

- Liquid hydrocarbons removed from the production stream but not from oil refining;

- Gases from the production stream, such as hydrogen sulfide and carbon dioxide, and volatilized hydrocarbons;

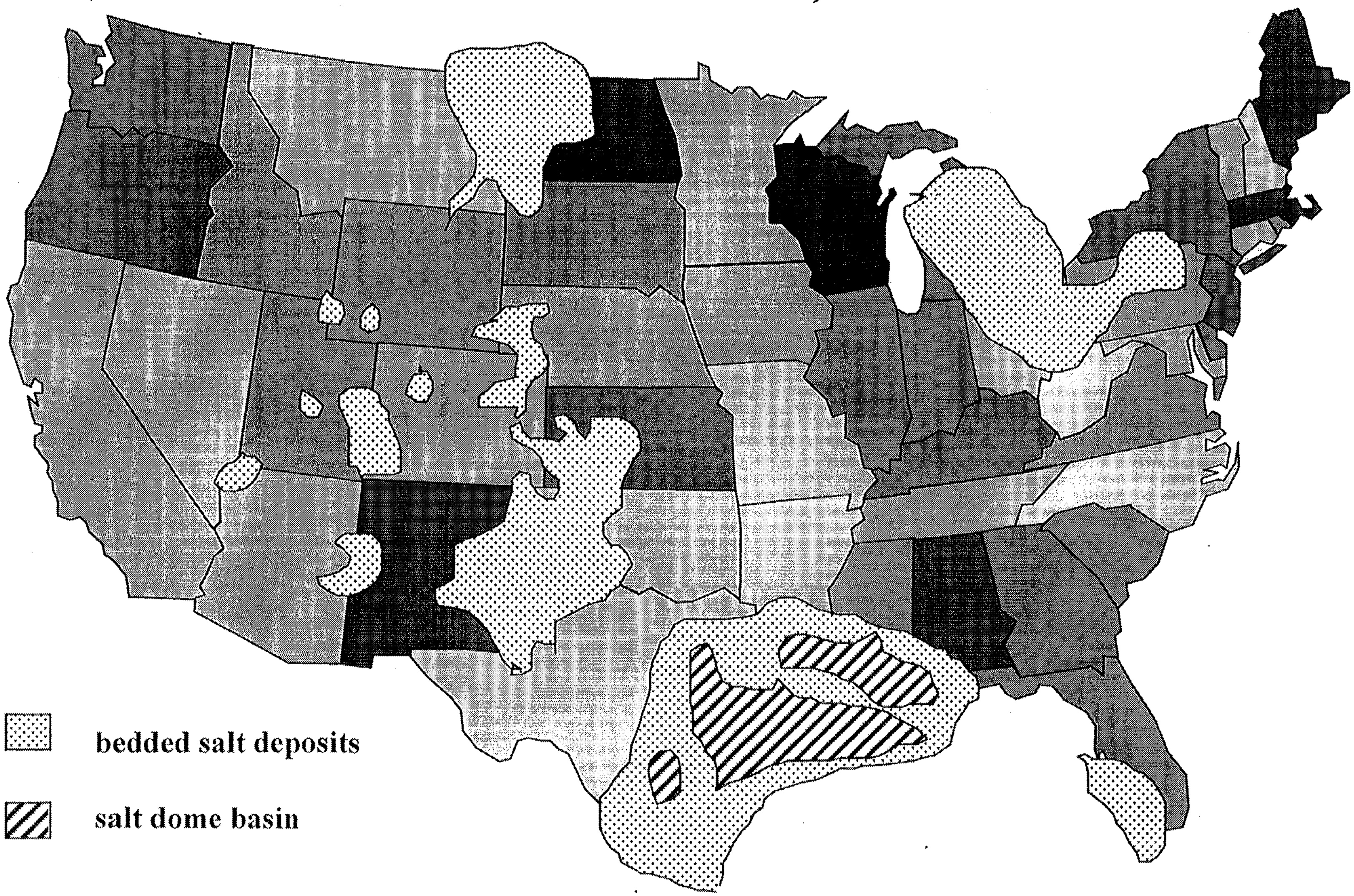
- Materials ejected from a producing well during the process known as blowdown;

- Waste crude oil from primary field operations and production; and

- Light organics volatilized from exempt wastes in reserve pits or impoundments or production equipment.

FIGURE 1 Major U.S. Subsurface Salt Deposits

(redrawn from Johnson and Gonzales 1978)



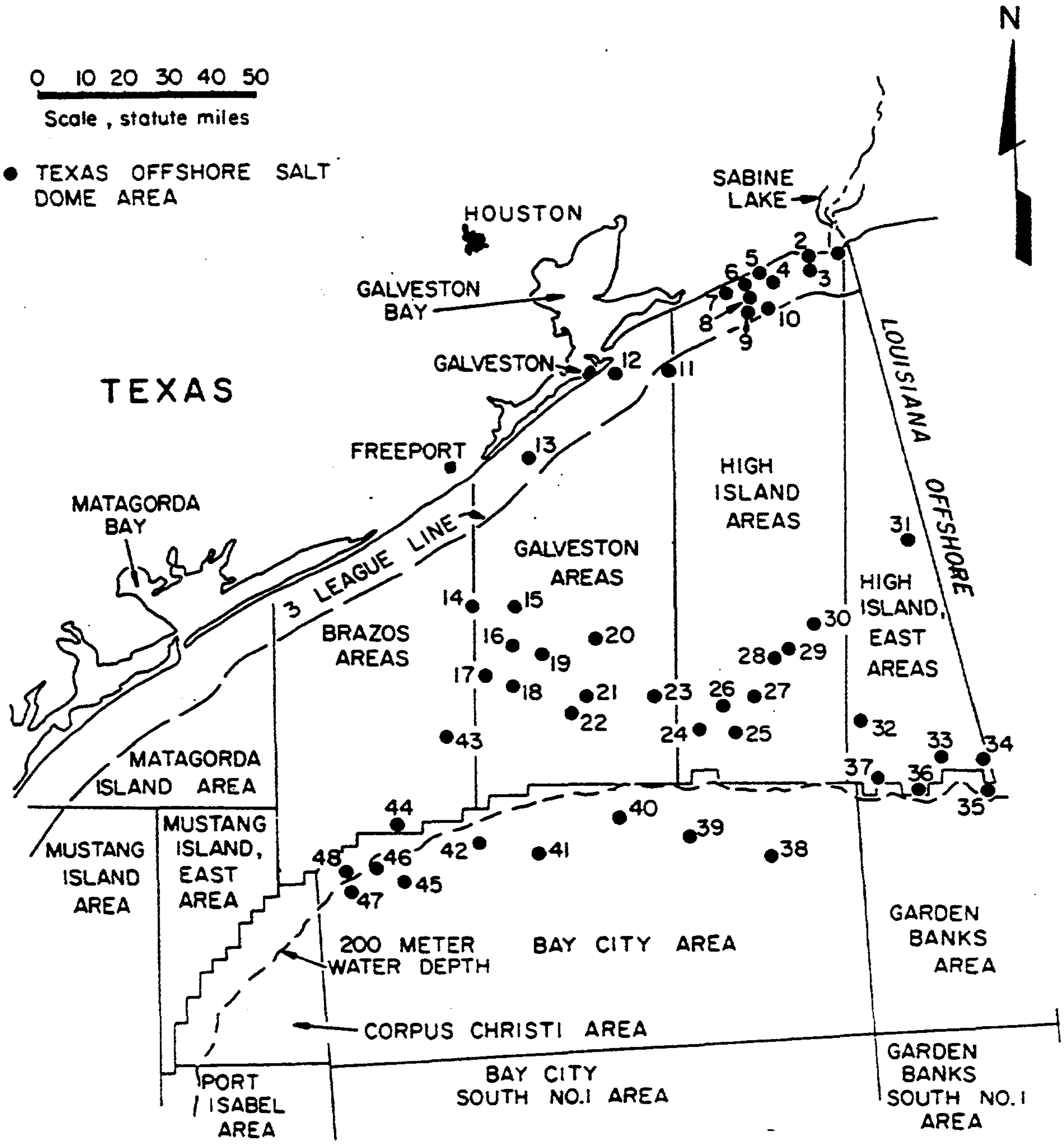


Figure 2 - Location of Texas Offshore Salt Domes (from Jirik and Weaver 1976)

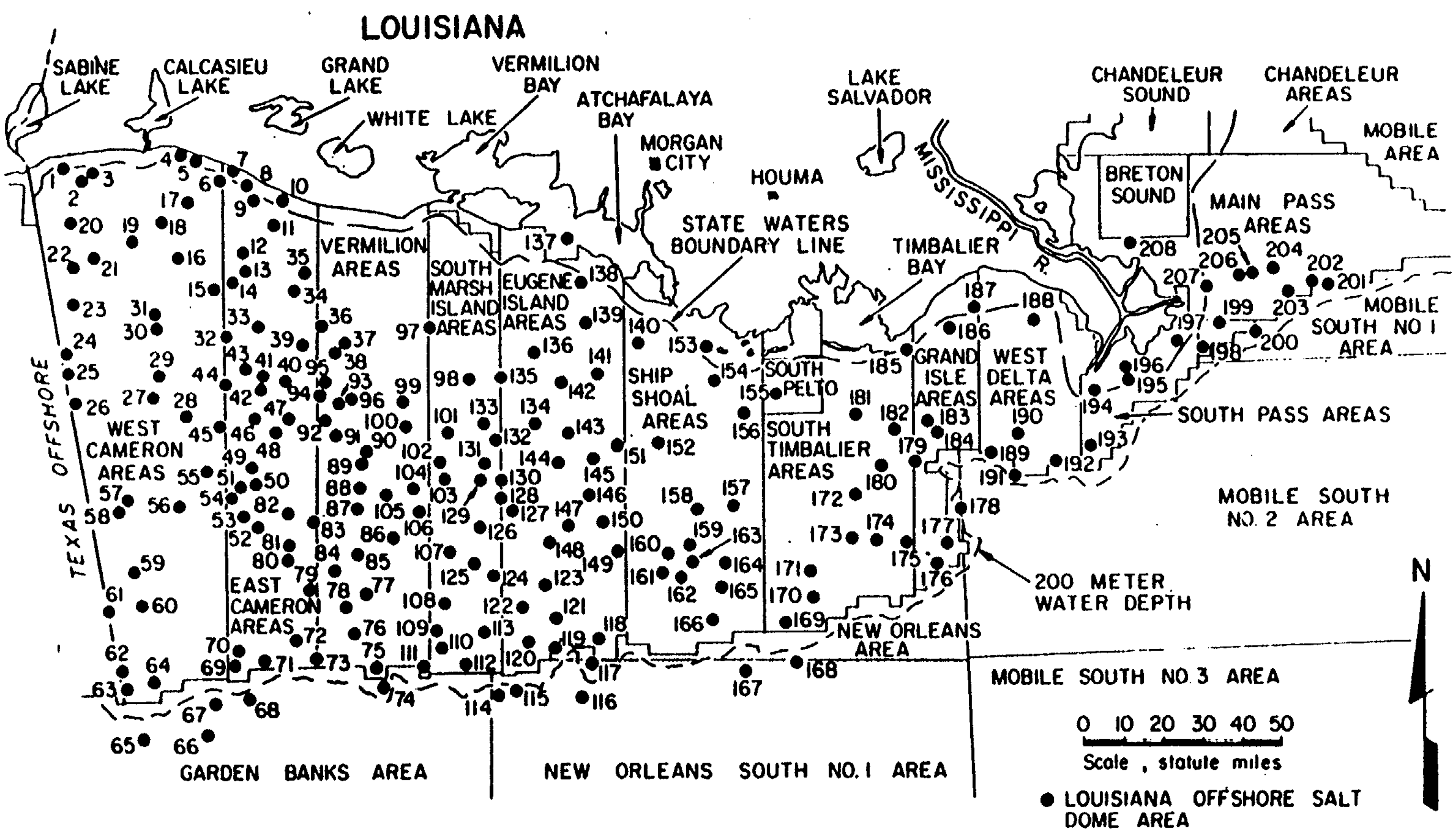


Figure 3 - Location of Louisiana Offshore Salt Domes (from Jirik and Weaver 1976)

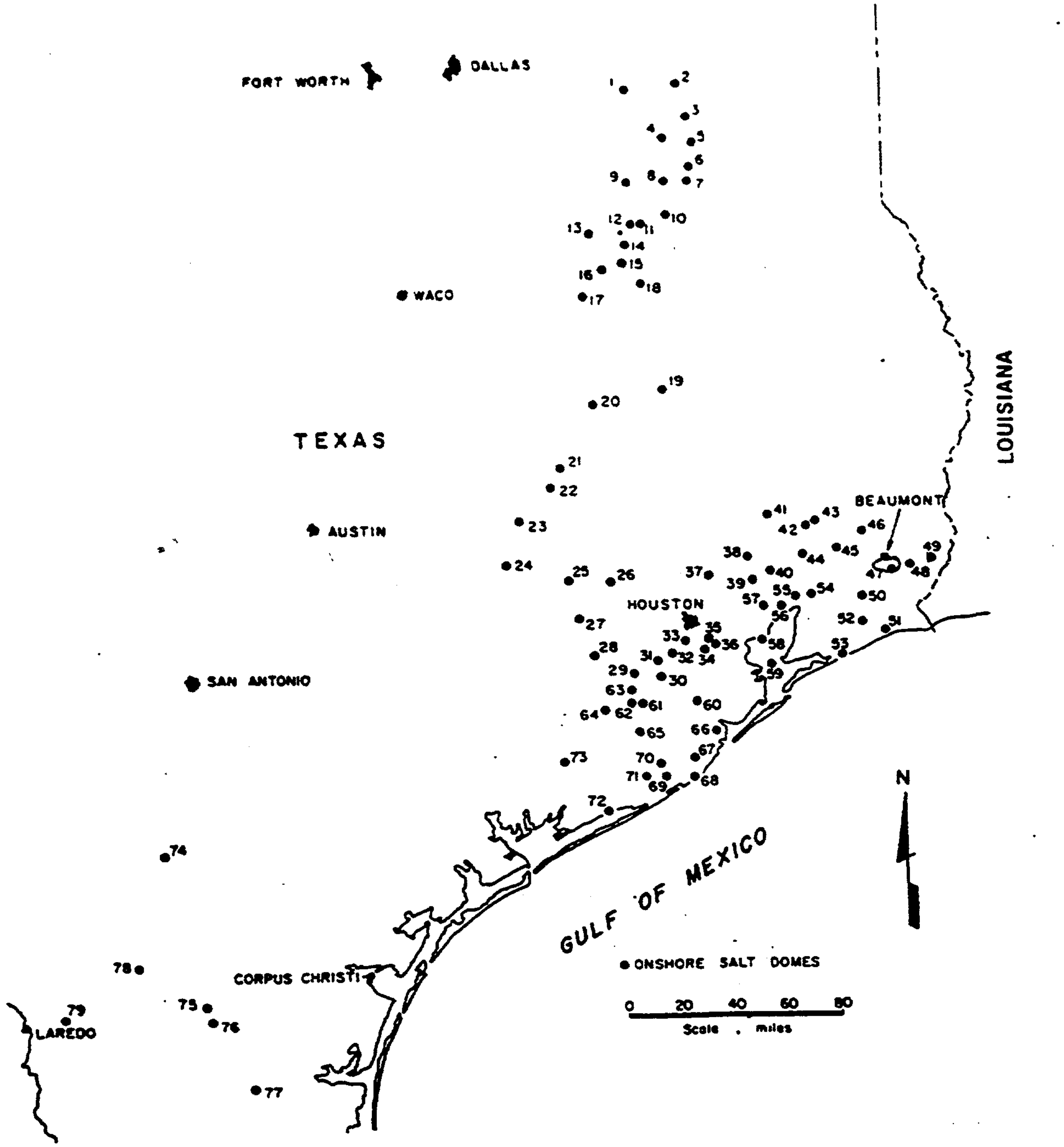


Figure 4 - Location of Texas Onshore Salt Domes (from Jirik and Weaver 1976)

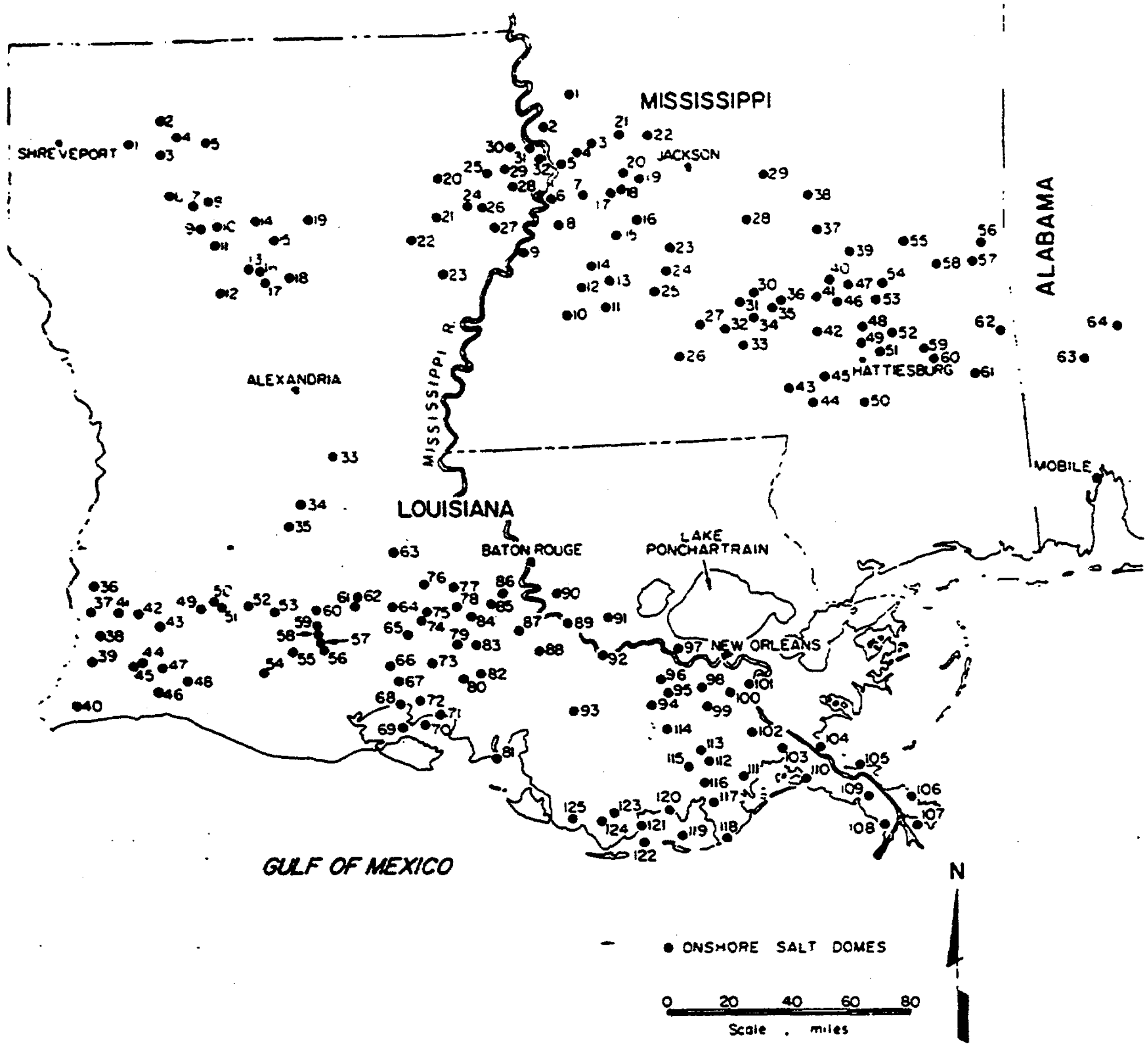


Figure 5 - Location of Louisiana, Mississippi, and Alabama Salt Domes (from Jirik and Weaver 1976)

Figure 6 - Idealized Cavern in a Salt Dome Formation (not to scale)

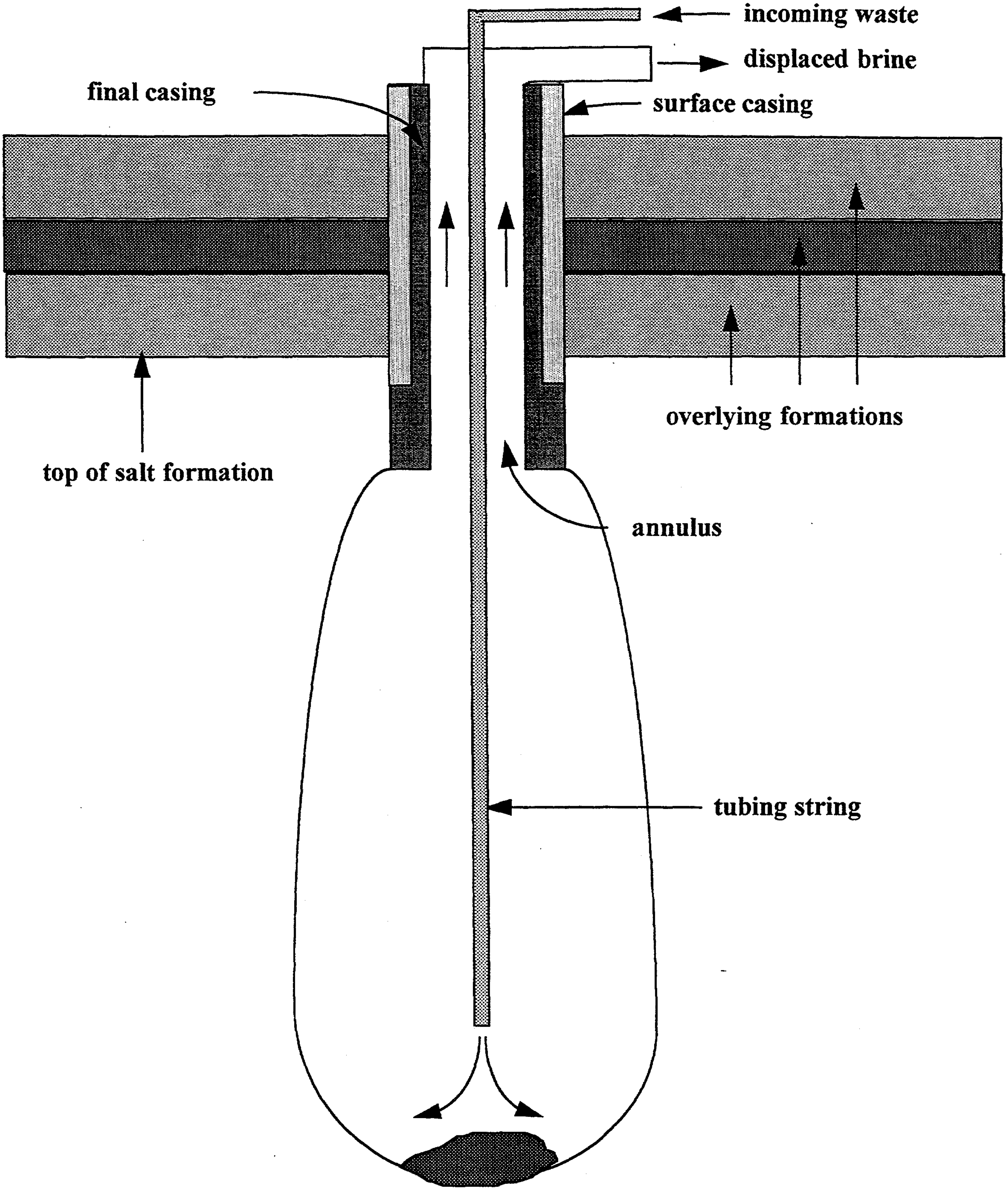


Figure 7 - Idealized Cavern in a Bedded Salt Formation (not to scale)