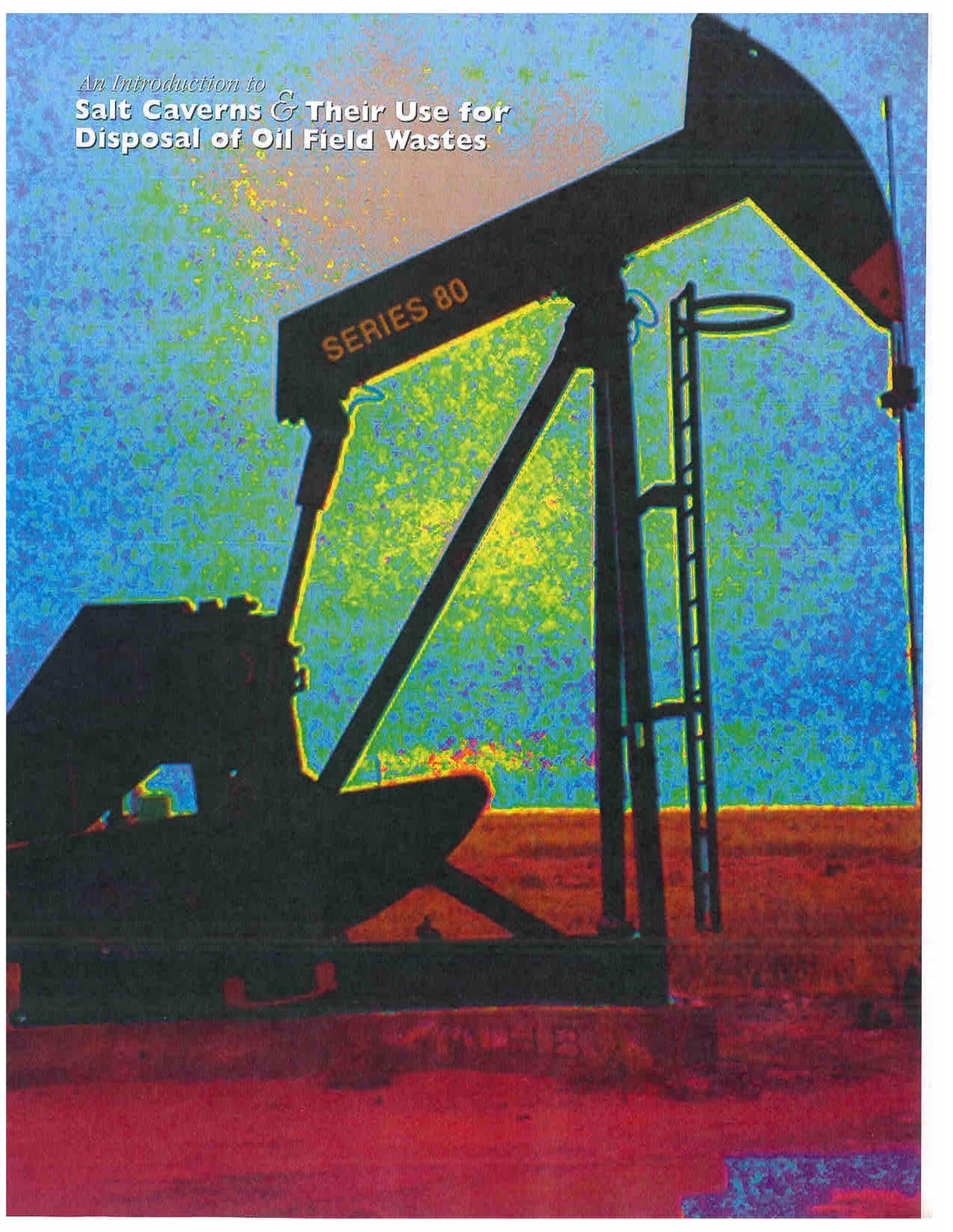
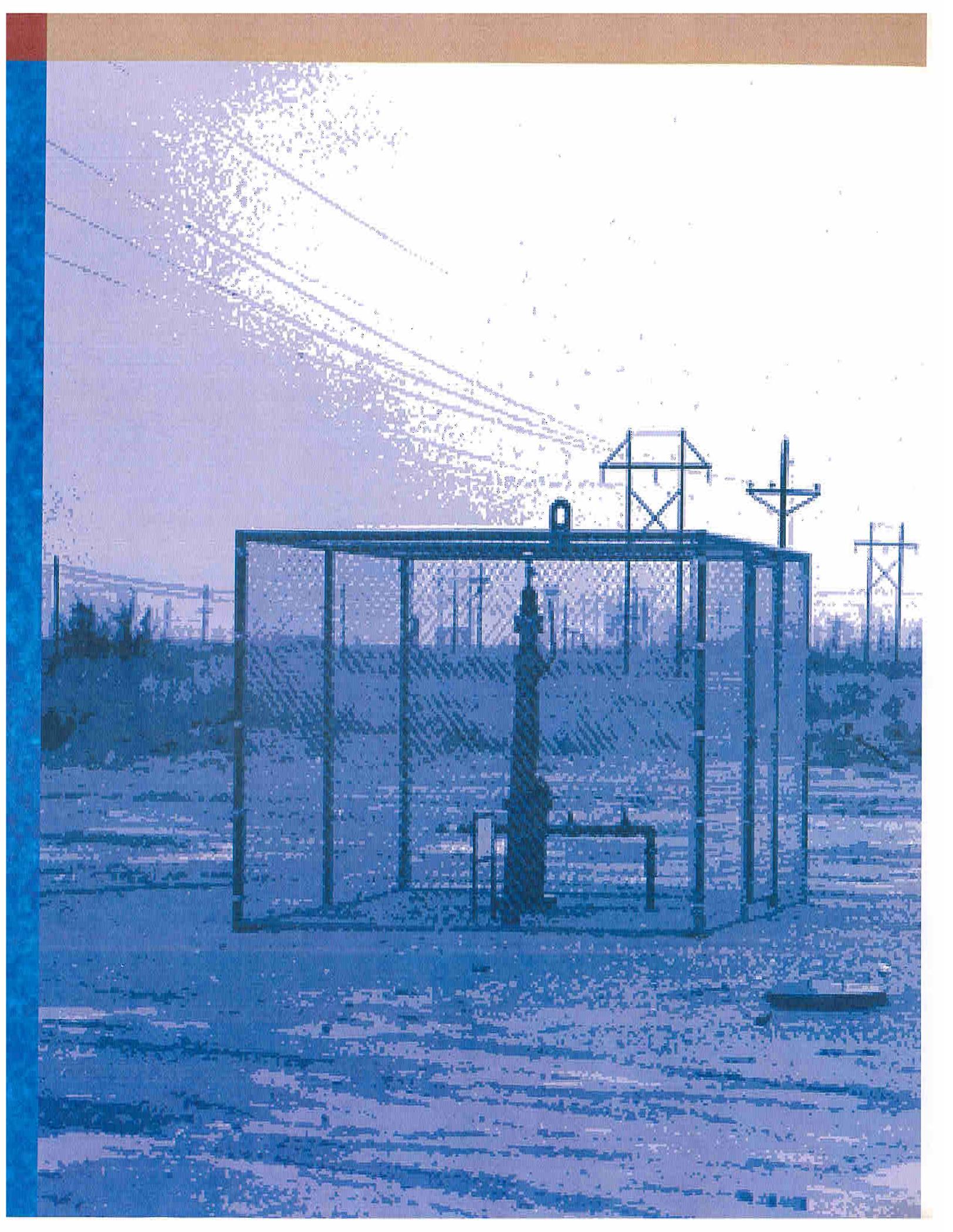


*An Introduction to*  
**Salt Caverns & Their Use for  
Disposal of Oil Field Wastes**





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*Inside Cover:  
Well Head at a West Texas Oil Field  
Waste Disposal Cavern*



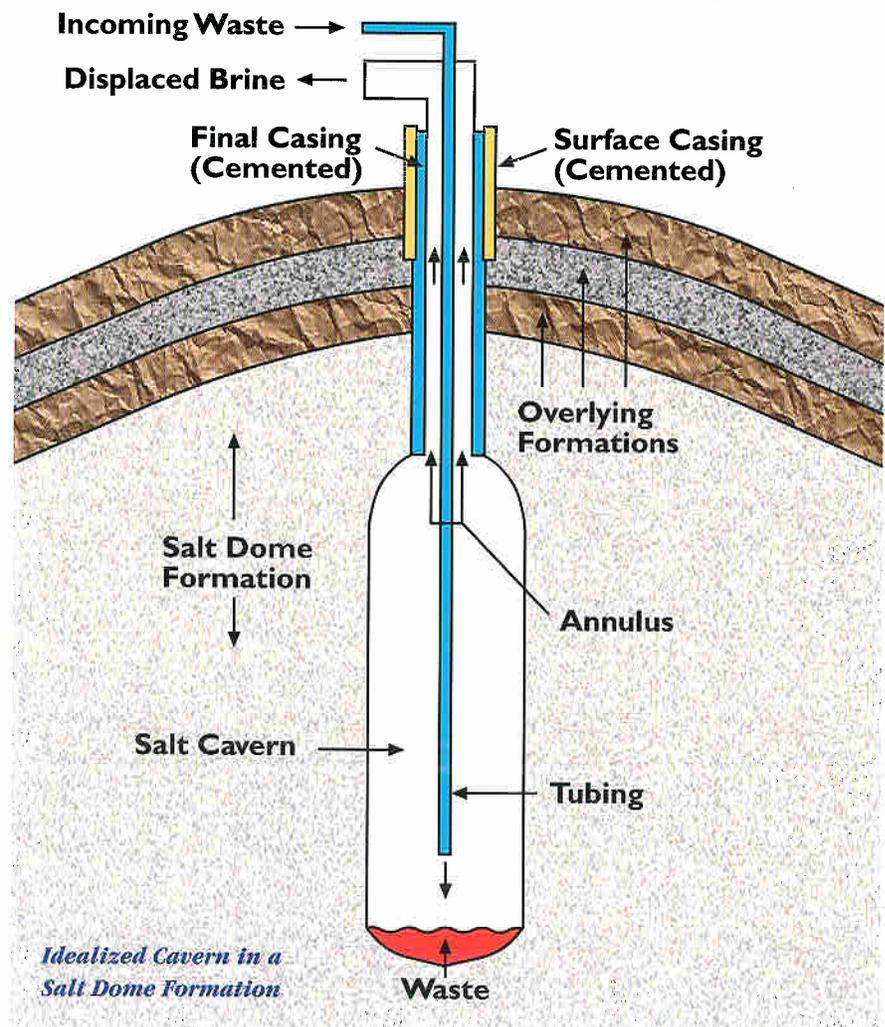
*About the Cover:  
West Texas Oil Field  
Pumping Unit*

## What Are Salt Caverns?

**S**alt caverns are cavities or chambers formed in underground salt deposits. Although cavities may naturally form in salt deposits, this brochure discusses caverns that have been intentionally created by humans for specific purposes, such as for storage of petroleum products or disposal of wastes.

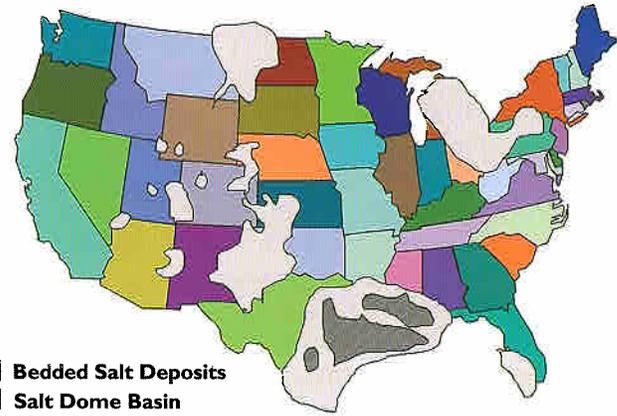
## Why Are Salt Caverns Important?

**B**ecause of the degree of protection they provide, salt caverns are used for hydrocarbon storage and are beginning to be used for disposal of oil field wastes. This brochure provides basic information on salt caverns and gives sources for additional information.

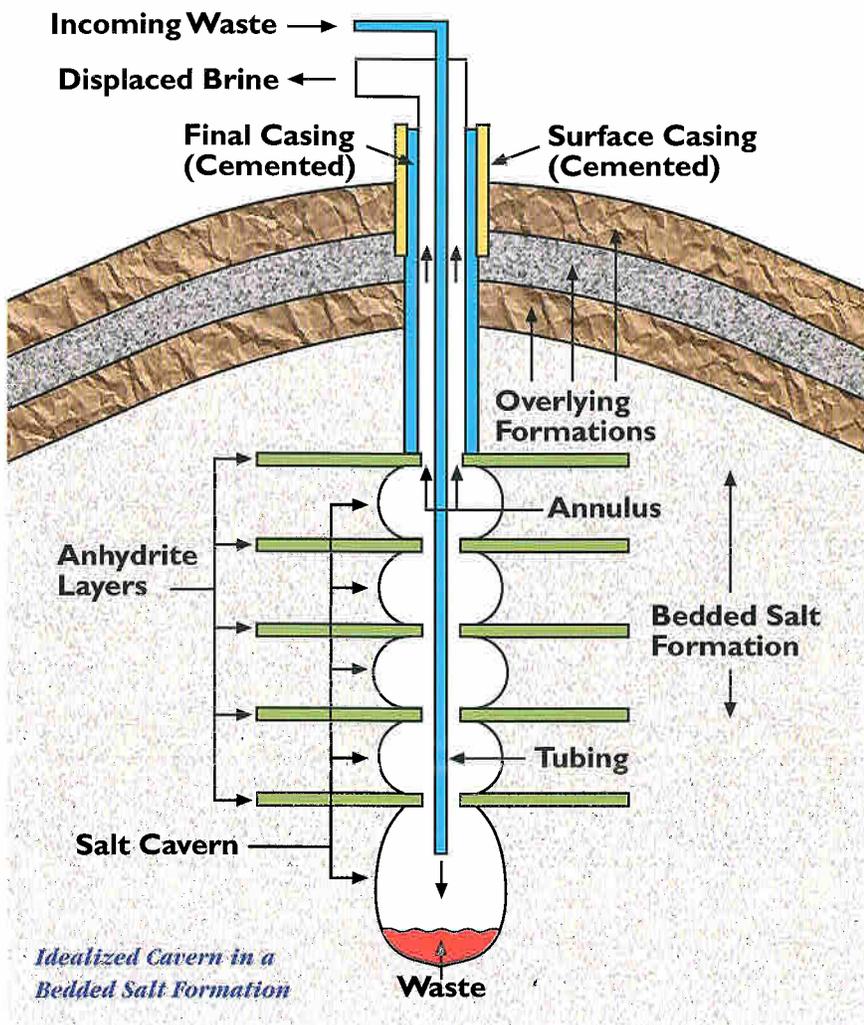


## Where Are Salt Deposits and Caverns Found?

**U**nderground salt deposits were formed naturally over millions of years and are found in many parts of the world. The map at right shows the locations of major salt deposits in the United States. Salt and other minerals precipitated when small oceans or seas evaporated, leaving behind bedded salt formations. Salt is a relatively weak and light rock. If buried by heavy overlying rock formations, salt will slowly flow and form salt domes. Salt domes are large, fingerlike projections of nearly pure salt that have risen to near the surface. As salt domes are formed, they often trap oil and gas and other minerals around their edges. The tops of salt domes can reach the surface or may be thousands of feet



*Major U.S.  
 Salt Deposit Locations*



*Idealized Cavern in a  
 Bedded Salt Formation*

below the surface. Salt domes range in width from 0.5 to almost 5 miles. In the United States, salt domes are found in Texas, Louisiana, and Mississippi, and in the Gulf of Mexico.

Bedded salt formations typically contain multiple layers of salt separated by layers of other rocks, such as shales, sandstones, dolomite, and anhydrite. Bedded salts often contain impurities. Salt beds occur at depths of 500 to 6,000 feet below the surface and are up to 3,000 feet thick. In the United States, bedded salts are primarily found along the Gulf Coast, through the central part of the country, and in the Great Lakes region.

More than 1,000 salt caverns have been intentionally created in these salt deposits in the United States. The intended use of a cavern and the nature of the salt formation in which it is formed determine a cavern's shape and size. Some caverns in salt domes are very tall and narrow, while some caverns in bedded salt formations may be short and wide or long tubes.

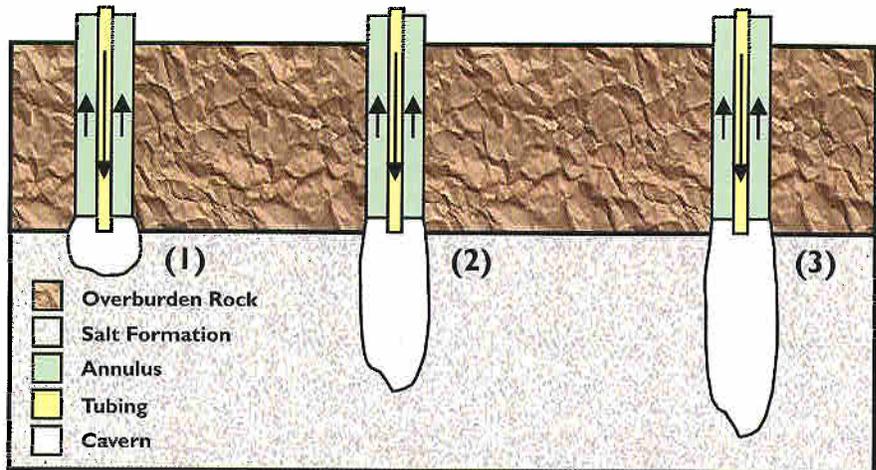
## How Are Caverns Formed?

**M**an-made salt caverns are formed through a process called solution mining. First, well-drilling equipment is used to drill a hole from the surface to the depth of the salt formation. The portion of the well above the salt formation is supported by several concentric layers of pipe known as casing to protect drinking water zones and to prevent collapse of the hole. A smaller-diameter pipe called tubing is lowered through the middle of the well. This arrangement creates two pathways into and out of the well – the hollow tubing itself and the open space between the tubing and the final casing (the annulus). To visualize how this works, think of a straw in a soft drink bottle. The straw represents the tubing, and the space between the straw and the bottle represents the annulus. Liquid can flow in or out of the bottle through both the straw and the annulus.

To form a salt cavern, the well operator pumps fresh water through one of the pipes. As the fresh water comes in contact with the salt formation, the salt dissolves until the water becomes saturated with salt. The salty brine is then pumped to the surface through the second of the two pipes. Cavern space is created by the removal of salt as brine. Operators typically use a combination of direct and reverse circulation, as shown in the figures to the right, at different times to create the desired cavern shape. Some operators install two wells in their caverns and can alternate injection of fresh water and brine withdrawal between the two wells to achieve the desired size and shape of the cavern.

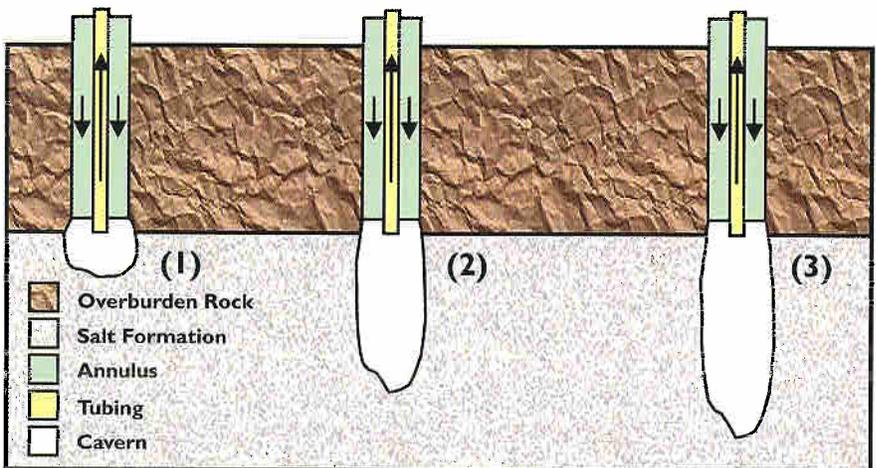
### Direct Circulation

Fresh Water Is Injected through Tubing, and Brine Is Withdrawn through the Annular Space between the Tubing and the Final Well Casing



### Reverse Circulation

Fresh Water Is Injected through the Annulus, and Brine Is Withdrawn through the Tubing

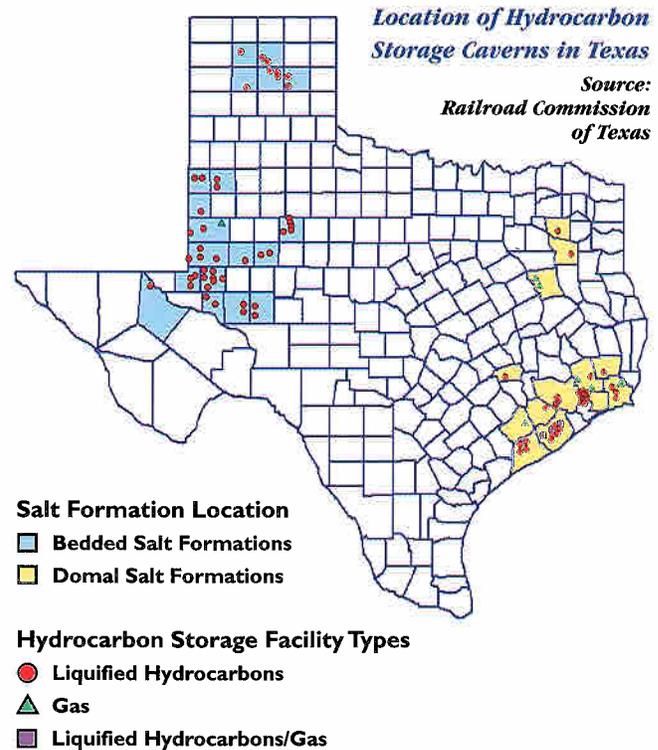


## How Are Caverns Used?

**Brine Production:** In this case, caverns are a by-product of brine production. As brine is produced, a cavern is created and enlarged. The solution mining process is regulated by federal and state agencies through the Underground Injection Control program. Brine can be sold for use in drilling fluids for drilling oil and gas wells or can be used to make salt or other chemicals. Once caverns have reached their maximum permitted size or can no longer be operated efficiently, brine production stops, and the caverns are either left filled with brine or are used for other purposes, such as storage or disposal.

**Hydrocarbon Storage:** Salt caverns have been used to store various types of hydrocarbons since the 1940s. The types of products that have been stored in these caverns include liquefied petroleum gas (LPG), propane, butane, ethane, ethylene, fuel oil, gasoline, natural gas, and crude oil. The largest underground storage operations in the United States are part of the U.S. Department of Energy's (DOE's) Strategic Petroleum Reserve (SPR). The SPR currently stores about 560 million barrels of crude oil in 62 caverns located at four sites in Louisiana and Texas. Efforts are underway to add another 28 million barrels of crude oil to these sites.

**Waste Disposal:** Salt caverns represent secure repositories located far below the earth's surface. Several proposals have been made in the United States, Mexico, and Europe to dispose of hazardous chemical wastes in salt caverns, but as of 1999, none have received regulatory approval. In the United States, the DOE, after years of careful study, opened its Waste Isolation Pilot Plant (WIPP), in a bedded salt formation in New Mexico. Although the WIPP was created through conventional mining techniques rather than through solution mining, DOE's



decision to place a nuclear waste disposal facility in bedded salt is an indication of the protection offered by salt formations.

In several countries, brine producers are allowed to dispose of impurities from the brine processing operations back into the caverns. One British company is authorized to dispose of inorganic and organic wastes from specific industrial processes into caverns.

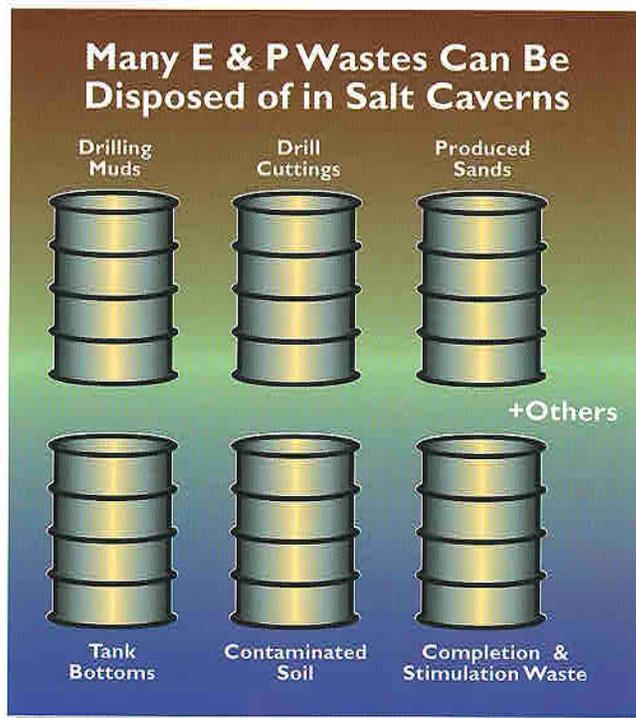
This brochure is primarily focused on the use of salt caverns for disposing of oil field wastes. The following sections summarize information from a series of four reports prepared for DOE by Argonne National Laboratory. The four reports cover (a) technical feasibility and legal issues, (b) costs, (c) risk, and (d) disposal of naturally occurring radioactive materials associated with oil field waste. Copies of these reports are available on Argonne's website at [www.ead.anl.gov](http://www.ead.anl.gov).

*Oil Field Waste Is Pumped into a  
West Texas Disposal Cavern*

## What Types of Wastes Are Considered to Be Oil Field Wastes?

The process of drilling oil and gas wells and pumping or producing oil and gas to the surface generates various types of wastes that must be disposed of in an environmentally secure manner. One such waste is the salty water that is brought to the surface along with oil and gas. Much of this “produced water” is reinjected to underground formations through injection wells. Other types of wastes that contain more oil or solids are less suitable for injection and are handled in different types of surface facilities. The types of wastes handled in this manner include drilling fluids, drill cuttings, produced sands, tank bottoms (solids or semisolids that settle in the bottoms of storage tanks), and soil contaminated by small leaks of crude oil. Many agencies refer to these various materials as “nonhazardous oil field wastes,” or NOW. Other agencies refer to them as E&P (exploration and production) wastes.

Some oil field wastes become contaminated with naturally occurring radioactive material (NORM). Produced water often becomes contaminated with the natural radiation in the formations holding oil and gas. As the produced water is brought to the surface and is handled there, radioactive pipe scale and sludge form, and soil may be contaminated by leaks of produced water. These NORM wastes have the same chemical and physical makeup as NOW, but also contain measurable radioactivity.



*Oil Field Pipe  
May Contain  
NORM Scale*

## What Are the Legal Requirements Governing Disposal of Oil Field Wastes into Salt Caverns?

State agencies have the lead responsibility for managing oil field wastes. The federal law covering waste management is the Resource Conservation and Recovery Act (RCRA). Under provisions of RCRA, the U.S. Environmental Protection Agency (EPA) establishes regulations to manage hazardous wastes. In 1988, EPA announced that wastes resulting from exploration and production of oil and gas were exempted from the hazardous waste requirements of RCRA. In other words, these wastes were considered to be nonhazardous. EPA concluded that existing state regulatory programs were generally adequate to control oil field wastes. Since 1988, state waste management programs have been strengthened. All state oil and gas agencies have NOW management requirements, and a few states also have NORM management requirements.

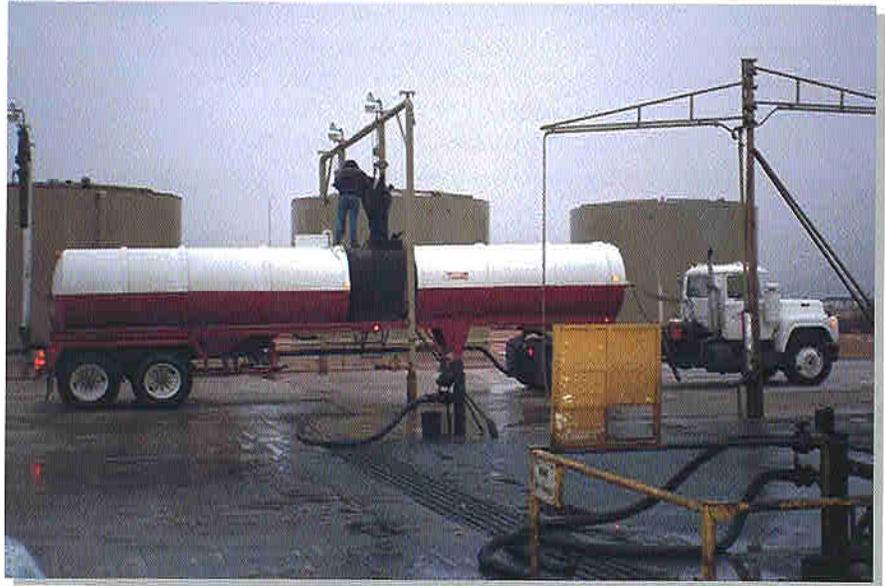


The Underground Injection Control (UIC) program, under the Safe Drinking Water Act, is a federal program that governs disposal of oil field wastes into salt caverns. Wells into which wastes and other fluids are injected are considered to be UIC wells. Injection wells used for disposal of oil field wastes are called Class II injection wells. Many state oil and gas agencies have assumed the authority from EPA to administer Class II injection well programs. These agencies develop state regulations and issue permits or other authorizations for oil field waste disposal. Texas, New Mexico, and Louisiana are currently developing regulations that will specifically govern disposal of oil field wastes into caverns.

*Washington, DC*

## Are NOW or NORM Wastes Currently Being Disposed of into Caverns?

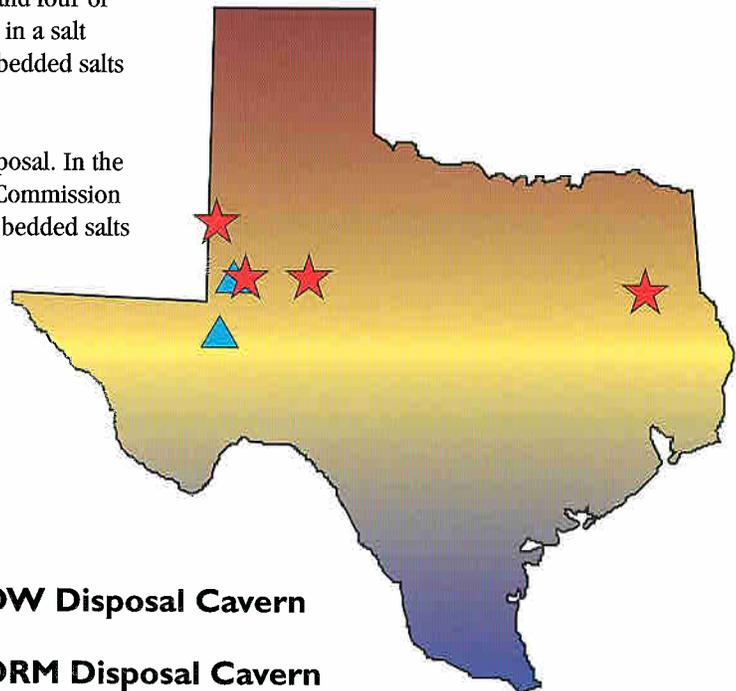
Some caverns have been approved for disposal of NOW and NORM wastes, but a number of conditions must be met. First, there must be a site with suitable salt formations. Second, the appropriate regulatory agency must give approval for the disposal cavern. Finally, the chosen site must be relatively close to where the waste is being generated. The cost of hauling NOW waste more than 50 to 100 miles becomes prohibitive. There are fewer approved NORM disposal sites, and the disposal costs are much higher; therefore, the cost of hauling in relation to the disposal cost is less important, and hauling distances can be greater.



*Tanker Loading Brine at a West Texas Cavern facility*

Several countries have authorized disposal of NOW into salt caverns. Saskatchewan and Alberta, Canada, have approved several caverns for NOW disposal. Germany has reportedly authorized NOW disposal caverns, and the Netherlands is considering allowing cavern disposal of oil field wastes. In the United States, the Texas Railroad Commission issued permits for six disposal caverns in the mid 1990s, and four of these went into operation. One operating facility is located in a salt dome in eastern Texas, and the other three are located in bedded salts in western Texas.

Until early 1999, no caverns were approved for NORM disposal. In the spring and summer of 1999, however, the Texas Railroad Commission issued two permits for cavern disposal of NORM wastes in bedded salts in western Texas.



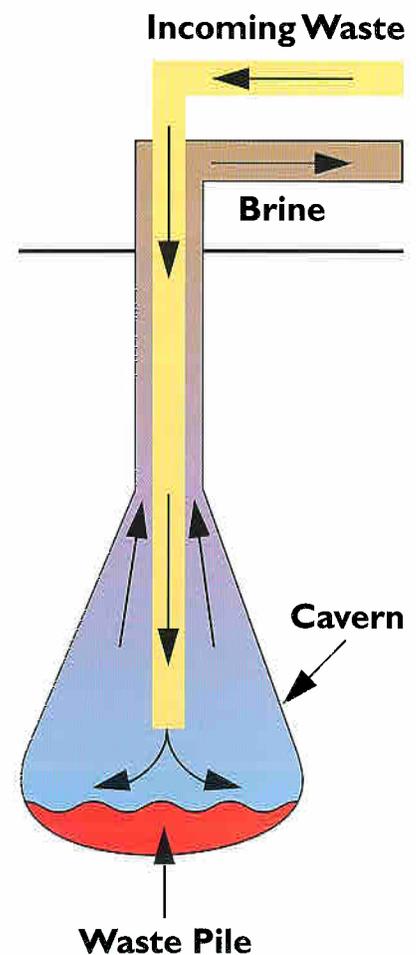
*Location of NOW and NORM  
Disposal Caverns in Texas  
(As of September 1999)*

## How Are Wastes Put into Caverns?

The process that creates caverns leaves them filled with brine. Wastes are brought to the cavern site in trucks and unloaded into mixing tanks, where they are blended with water or brine to make a slurry. Grinding equipment may be used to reduce particle size. The waste slurry is then pumped into the caverns. Each barrel of waste slurry pumped into the cavern displaces a barrel of brine back to the surface. This brine can be sold, if a market exists and the state regulatory agency allows such sales, or can be injected underground in a Class II disposal well.



*Waste Blending and Mixing at a West Texas Disposal Cavern*



*Waste Emplacement Process*

Among the four operating disposal caverns in Texas, three different waste loading practices are followed. Two caverns are operated by injecting wastes through the well tubing and withdrawing brine through the annulus. One cavern operator injects wastes through the annulus and withdraws brine through the tubing. The fourth cavern uses two wells – one to inject waste and the other to remove brine.

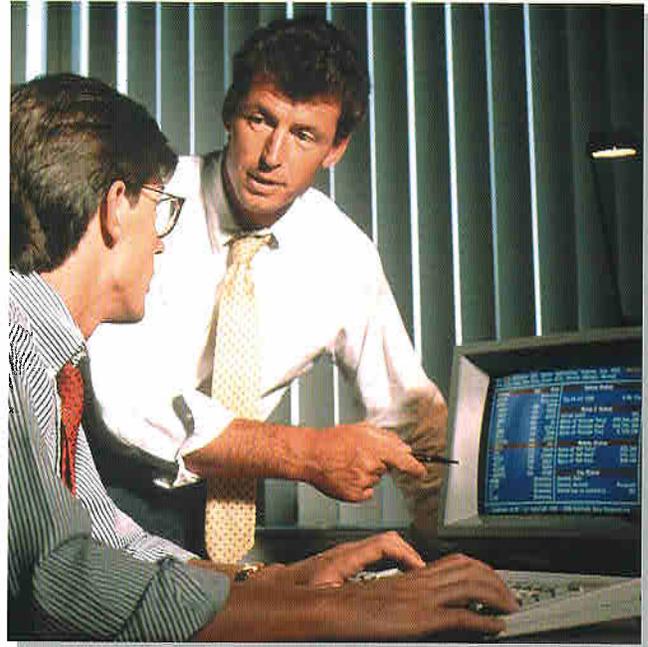
Inside the cavern, the solids, oils, and other liquids separate into distinct layers, much like in a bottle of Italian salad dressing. The solids fall to the bottom and form a pile, the oily materials float to the top where they form a protective pad, preventing unwanted dissolving of the cavern roof. The brine and other watery fluids remain in a middle layer.

## What Types of Monitoring Are Appropriate for Disposal Caverns?

To ensure the safe and efficient use of a disposal cavern, it is important to have information on the volume and types of waste that are placed into the cavern, including information on the levels of solids, oil, and water. The water content is important because any water that is not already fully saturated with salt will dissolve away some of the salt from the cavern walls, thereby enlarging the cavern. Cavern enlargement is not a problem, as long as the cavern operator keeps track of how much water is added and how much space is created.

It is also useful to have information about the cavern shape and size. Such information can be obtained by various monitoring methods, such as sonar, that give an indication of the interior dimensions of the cavern.

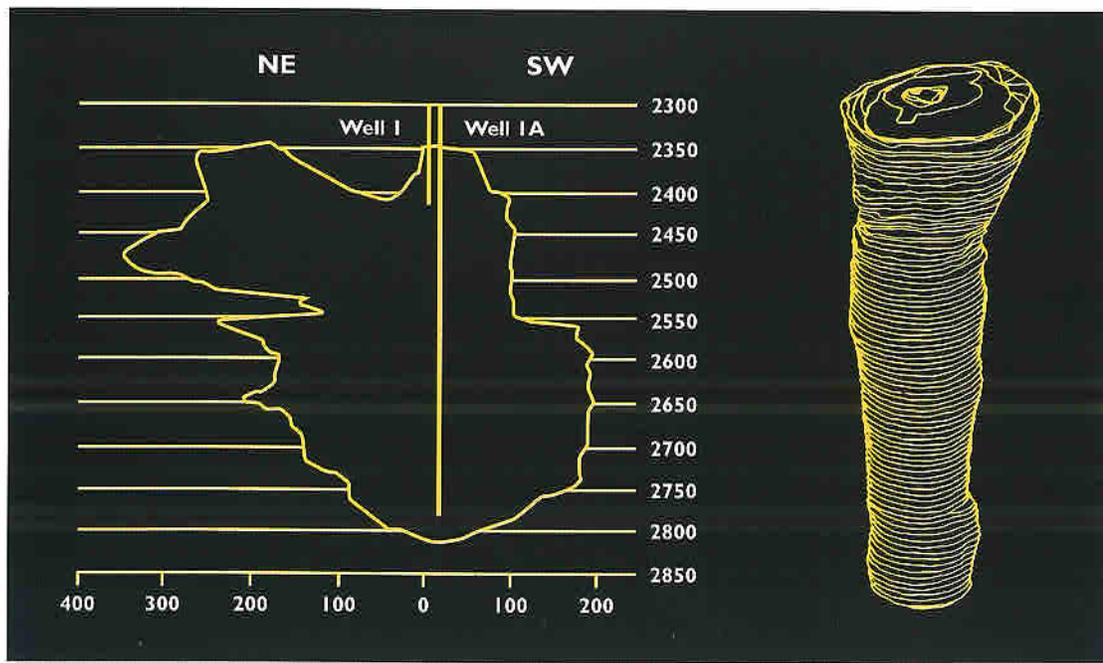
Another important parameter for monitoring is the internal cavern pressure. Pressure should be monitored before the cavern is filled with waste, while the cavern is being filled, and after the cavern is filled.



*Review of Monitoring Data Helps to Ensure Safe Cavern Operations*

### *Sonar Monitoring Provides Two- and Three-Dimensional Views of Cavern Size and Shape*

*(Note: These Images Come from Two Different Caverns)*



## What Happens to the Cavern When It Is Full?

Once the cavern has been filled with waste, the operator will remove the oily layer floating at the top of the cavern, plug the well leading to the cavern, and permanently seal the cavern. During the cavern filling process, the pressure used to inject the waste into the cavern is relatively low. However, once the cavern has been sealed, internal cavern pressure will increase for two reasons. First, the weight of the overlying rock causes the salt formations surrounding the caverns to deform and press against the cavern walls. The salt then slowly flows into the cavern, reducing its volume. This process is known as salt creep. Second, because the temperature of the rocks surrounding the cavern increases with depth, geothermal energy heats the cavern contents, causing them to expand.



Both of these processes cause the internal cavern fluid pressure to rise. Some researchers have suggested that the pressure will increase to a point that the cavern walls crack or leak. Limited field data indicate that even though salt is very nonporous under normal circumstances, when it is subjected to very high pressures, small quantities of fluids from the caverns may migrate into the salt formation surrounding the cavern, thereby relieving the cavern pressure. Since no disposal caverns have been closed anywhere in the world, no actual data exist to show how a disposal cavern will behave following closure. Additional laboratory and field research is underway that will define the extent and effects of the pressure rise.

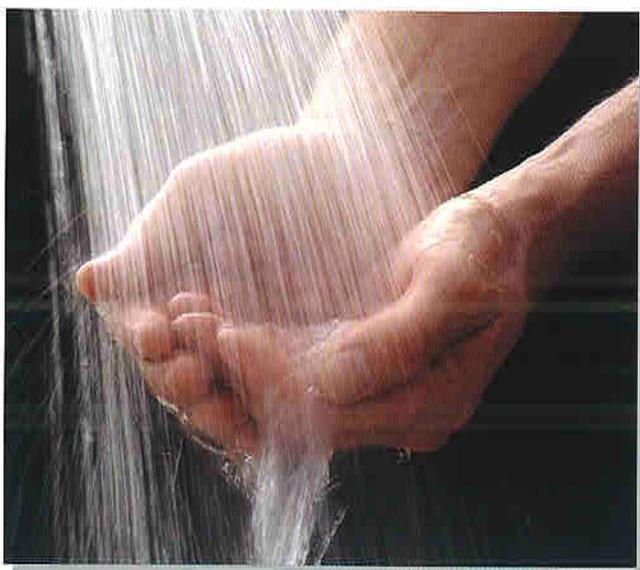
*Injection Pump at a West Texas  
Disposal Cavern Facility*

## What Would Happen If Caverns Leak?

**B**ecause the issue of whether caverns will leak after they are closed has not been resolved, DOE asked Argonne to predict how caverns might leak and what would be the effects on humans who might drink water contaminated by wastes from cavern leaks.

### How Might Caverns Leak?

1. A new well could inadvertently be drilled into an old, closed disposal cavern. Some portion of the cavern fluids might mix with the drilling fluids of the well being drilled and be circulated to the surface pit or tank. They might then overflow to the land surface.
2. The plug in the closed cavern well could fail, and fluids could begin moving up the well bore. Fluids could escape if they moved upward behind the well casing or out through holes in the casing either near the depth of the cavern or nearer the surface.
3. Fluids could escape through the sides of the caverns through cracks or, in bedded salts, through the more permeable rock layers between the salt layers.
4. The roof of the cavern could collapse, allowing the cavern fluids to escape. Fluids could move up the well bore and be released at the top of the cavern or nearer the surface.



### How Often Will Caverns Leak?

No information is available on the likelihood that any of these events might happen. A group of experts was asked to estimate, on the basis of their knowledge and experience, the probability of each type of failure. These numbers were averaged. To give an indication of the absolutely worst possible situation, Argonne also evaluated a case under which all caverns were assumed to fail.

Type of Leak Event	Probability	
	Most Likely	Least Likely
Inadvertent Intrusion	0.008	0.017
Plug Failure – Deep Leak	0.031	0.120
Plug Failure – Shallow Leak	0.012	0.040
Cracks/Leaky Interbeds	0.022	0.120
Roof Collapse – Deep Leak	0.062	0.163
Roof Collapse – Shallow Leak	0.006	0.051
Roof Collapse – Deep Leak, Plug Intact	0.100	0.290

### What Would Happen to Fluids after They Left the Cavern?

If fluids actually left the cavern, it is assumed that they would begin migrating horizontally away from the cavern and could mix with groundwater used for drinking water. Argonne assumed that the first point of human contact would be at a drinking water well located 1,000 feet away from the cavern. Assumptions were made about how rapidly the groundwater would flow toward the well. As the cavern fluids passed through the soils and rocks, various chemical, biological, and physical processes would change the concentration and makeup of the groundwater such that the water eventually reaching the drinking water well would contain a much lower concentration of contaminants than was originally present in the fluids leaving the cavern. Most of the radiological components of NORM wastes would become bound up by soils and rocks such that only very low concentrations of those components would ever reach the drinking water well.

*Disposal Cavern Operations Must  
 Protect Drinking Water Quality*

## What Are the Risks Posed by Leaks from Caverns?

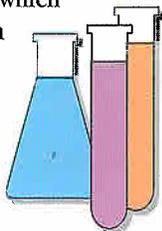
Argonne estimated the cancer and noncancer risks to humans from drinking water contaminated by fluids leaked from disposal caverns.

*Well Heads at a West Texas  
Disposal Cavern*



### Cancer Risks

The EPA has established an acceptable cancer risk level of  $10^{-4}$  to  $10^{-6}$ . Risks lower than these levels are considered to be safe. A risk of  $10^{-6}$  means that the event causes one additional cancer case per 1 million persons exposed. As an example of how to interpret these numbers, an event with a risk of  $10^{-4}$  is 100 times more risky than an event with a risk of  $10^{-6}$ . Using the very worst case situation, in which all caverns fail, the estimated cancer risk from NOW and NORM wastes is only  $10^{-7}$  to  $10^{-16}$ . The risk from the radiological components of NORM waste is many times lower at  $10^{-13}$  to  $10^{-22}$ . These levels are all below the EPA's acceptable risk range.



### Noncancer Risks

Leaks from disposal caverns might pose additional health risks through causes other than cancer. EPA uses a different methodology, the hazard index, to evaluate these noncancer risks. In this case, EPA's acceptable risk level is a hazard index of less than 1.0. Using the scenario in which all caverns fail, the estimated noncancer risk from NOW and NORM wastes is a hazard index of  $10^{-3}$  to  $10^{-7}$ .

These estimates suggest that cavern disposal poses very low human health risks, even if all caverns leak. The radiological risk, while perceived by the public to be more serious, is actually many orders of magnitude lower than the already low chemical risk.

## How Do Disposal Caverns Compare in Cost?

**D**isposal costs at the four operating NOW disposal caverns in Texas are comparable to or lower than the costs at other types of commercial NOW disposal facilities. The 1997 cavern disposal costs ranged from \$1.95 to \$6.00 per barrel (bbl) of waste. The 1997 costs at competing Texas and New Mexico commercial treatment facilities are shown below:



Disposal Method	Cost (bbl)
Land Spreading	\$5.50 – \$16.00
Landfill or Pit Disposal	\$2.25 – \$3.25
Evaporation	\$2.50 – \$2.75
Treatment and Injection	\$8.50 – \$11.00
<b>Cavern Disposal</b>	<b>\$1.95 – \$6.00</b>

*Unloading Area at a  
West Texas Cavern Facility*



Most oil field NORM is sent to commercial disposal companies that charge more than \$100/bbl to dispose of NORM wastes. It is likely that cavern operators can charge that amount or less for NORM disposal and still be profitable.

# Where Can You Get More Information about Salt Caverns?

## U.S. Department of Energy



**D**OE's National Petroleum Technology Office (NPTO) has established a Salt Cavern Information section on its website. The address for that website is:  
<http://www.npto.doe.gov/saltcaverns>.

The website provides more detailed information on the topics covered in this brochure and provides links to other useful websites. The NPTO official responsible for salt cavern issues is John Ford; he can be reached by telephone at 918-699-2061 and by e-mail at [jford@npto.doe.gov](mailto:jford@npto.doe.gov).

DOE's Strategic Petroleum Reserve (SPR) office operates large salt caverns for crude oil storage. Information on SPR's operations is available at <http://www.spr.doe.gov>.

## The State Agencies that Are Developing Salt Cavern Regulations Are:



Railroad Commission of Texas  
 Oil and Gas Division  
 P.O. Box 12967  
 Austin, TX 78711-2967  
[www.rrc.state.tx.us](http://www.rrc.state.tx.us)



New Mexico Energy, Minerals, and Natural Resources Department  
 Oil Conservation Division  
 2040 S. Pacheco Street  
 Santa Fe, NM 87505  
<http://www.emnrd.state.nm.us/ocd/>



Louisiana Department of Natural Resources  
 Office of Conservation  
 P.O. Box 94275  
 Baton Rouge, LA 70804-9275  
<http://www.dnr.state.la.us/CONS/Conserv.ssi>

## Research Organizations

Several leading research organizations – Argonne National Laboratory, Sandia National Laboratories, the Solution Mining Research Institute (SMRI), and the University of Texas - Bureau of Economic Geology (BEG) – formed the Salt Cavern Research Partnership. For more information about those organizations' salt cavern research programs, contact the following persons:

Organization	Name	Phone	E-mail
Argonne	John Veil	202-488-2450	<a href="mailto:jveil@anl.gov">jveil@anl.gov</a>
Sandia	Jim Linn	505-844-6813	<a href="mailto:jklinn@sandia.gov">jklinn@sandia.gov</a>
SMRI	Bill Diamond	858-759-7532	<a href="mailto:smri@solutionmining.org">smri@solutionmining.org</a>
BEG	Jerry Mullican	512-471-9262	<a href="mailto:mullicanj@begv.beg.utexas.edu">mullicanj@begv.beg.utexas.edu</a>

The Argonne National Laboratory reports that provide much of the baseline information on oil field waste disposal in salt caverns discussed here can be downloaded from the Argonne website at <http://www.ead.anl.gov> or obtained by calling 202-488-2450.

The other three research organizations have also compiled an extensive body of geological and engineering research on various aspects of salt formations and salt caverns.

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**Salt Caverns & Their Use for  
Disposal of Oil Field Wastes**



This brochure was produced by Argonne National Laboratory for the U.S. Department of Energy, National Petroleum Technology Office, Under Contract W-31-109-Eng-38 and is intended for educational purposes.

*Inside Cover:  
Well Head at a West Texas  
Oil Field Waste Disposal Cavern*



September 1999

