National Strategic Petroleum Reserve

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The Strategic Petroleum Reserve (SPR), authorized by law in 1975, was established to reduce the vulnerability of the United States to any severe interruption of imported oil supplies (1). The federal government considers the SPR the most effective means for reducing the cost to the nation of disruptions in the world oil market. The reserve's importance has increased concomitantly with worsening of the world's oil outlook.

Summary. The Strategic Petroleum Reserve is intended to reduce the vulnerability of the United States to interruptions in the oil supply from foreign sources. Storage for 248 million barrels of crude oil in salt caverns and mines, with equipment for pumping and distribution, was constructed and operationally tested in a 4-year period. Its present inventory is the largest known crude oil reserve in the world. Facilities for expanding the reserve's capacity by another 290 million barrels are being developed by solution-mining in salt domes.

The SPR was created to serve as a secure national storage for petroleum, our major source of energy. Storage facilities for up to 1 billion barrels of oil were authorized by the Energy Policy and Conservation Act of 1975, and plans for implementing storage facilities for 750 million barrels (MMB) were completed by 1978 (2). Since 1975, the world's largest complex of salt caverns and mines has been constructed, with a storage capacity of 248 MMB of oil. These caverns are provided with oil and water pumping and handling equipment and connected by pipeline to shipping terminals and to the national network of oil distribution pipelines.

Close to 200 MMB of oil is now stored in 16 salt caverns and a salt mine in Texas and Louisiana. Twenty-nine more caverns are being developed, and two brine disposal pipelines are now operating off the coast of Texas and Louisiana. Operational tests in February and April 1980 demonstrated the capability of the existing SPR complex of storage sites, terminals, and pipelines to meet the performance objectives of pumping out and transporting (drawing down) 1 MMB of oil in a 24-hour period. All of this construction, testing, and filling was done within a 4-year period (3).

To understand the engineering challenge of developing a 1-billion-barrel oil reserve, one must appreciate what this amount of petroleum represents. While crude oil is not generally transported in railroad tank cars, they are a familiar unit of measurement. For example, to store or transport 1 billion barrels of oil would require 4,200,000 average size (240 barrels each) tank cars comprising a train some 32,000 miles long. Once the oil is stored, the engineering challenge requires development of a capacity to withdraw and distribute the stored petroleum at a rate of 4 to 5 MMB per day. Stated in terms of railroad tank cars, this rate is equivalent to one tank car passing a fixed point every 4 to 5 seconds over a 6-month drawdown period. While industry has long practiced the art of storing petroleum products, crude oil has never been stored underground in such large quantities, with intent to store for such long periods of time, or maintained in a state of constant readiness for drawdown and distribution at such high rates.

Storing Petroleum

Types of petroleum—crude and refined products. Petroleum can be stored as crude oil or as a refined product such as gasoline, diesel fuel, or heating oil. Crude oil can be stored for longer periods than some of its refined products, which can be kept for only several months to 1 or 2 years, after which they must be either used or preserved with additives (4, 5). These refined products contain unstable chemical compounds which are produced during the refining process and are not indigenous to crude oil in its natural state. For this reason, as well as to provide increased product slate flexibility, crude oil was selected for storage in the SPR.

Even after the government's decision to store crude oil rather than refined products had been made, further decisions were needed on the types of crude oil to be stored in the SPR. Crude oils from different oil fields have different physical and chemical characteristics; two of primary importance are specific gravity and sulfur content. Because of such varying characteristics, it is not generally desirable to mix different crude types. Also, some refineries can accept only certain types of crude oil because of their limited capacity to "crack" the heavier products produced or their limited capability to reduce the sulfur content.

On the basis of realistic national scenarios, a mix of crude oil types was selected for storage in the SPR. It included two types of sour crude (high sulfur content) and four types of sweet crude (low sulfur content).

About 60 percent of the crude oil to be stored in the SPR is characterized by an intermediate American Petroleum Institute gravity (32 to 36 degrees API) and a sulfur content of 1.0 to 1.9 percent. The remainder has less than 0.5 percent sulfur and an intermediate to very high API gravity. The mix of crudes identified for storage in the SPR will permit the reserve to respond effectively to a wide range of possible interruptions to our national oil supply; it will also ensure that U.S. refineries have available an acceptable type of crude oil to replace restricted imports. While Alaskan North Slope crude oil, a relatively sour crude being stored, cannot be used by some refiners because of its high content of residuum, it can be commingled with certain other crudes to produce a stream which will yield the desired product slate.

Experience in the United States with underground storage of crude oil. Crude oil can be stored in aboveground steel tanks, underground concrete tanks, floating barges and tanks, rock caverns (igneous, metamorphic, and sedimentary), and lined surface pits (bladders). Aboveground storage has the advantage that it can be sited almost everywhere. It is also easy to move oil from aboveground tanks into pipelines or tankers for transport. A disadvantage of aboveground storage is its relatively high cost compared with that of underground tank storage. In 1981 dollars, costs for above-

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ground tank storage range from $12 to $18 per barrel, whereas underground storage costs experienced by the SPR have been less than $4 per barrel (*3*).

As early as 1909, the U.S. Geological Survey recommended that excess natural gas be stored underground. The first successful natural gas storage in the United States was in New York State in 1916 in an abandoned natural gas reservoir. Liquefied petroleum gases have been stored in salt strata since 1941 and in salt domes since 1951. The first solution-mined salt cavity for propane and butane storage in the United States was constructed at Keystonefield in western Texas. Propane, butane, ethane, ethylene, fuel oil, and a variety of mixed products, including natural gasoline and natural gas liquids, have all been stored in underground salt structures (*6*).

Over the past 25 years, underground petroleum product storage capacity in the United States has increased dramatically, from 29 MMB in 1957 to 106 MMB by 1965, 305 MMB by 1975 (*7*), and 411 MMB by 1979 (*8*). It is important to note that these products are cycled regularly—for example, seasonally.

Underground storage of crude oil, however, was not widespread in the United States at the time for decisions in 1975. Even today such storage is minimal. The first major industrial underground storage facility for crude oil, which will ultimately provide storage for 32 MMB, is being developed in the Clovelly salt dome in conjunction with the Louisiana Offshore Oil Port (LOOP). The uncertainties in the development of the SPR can be better understood when one realizes what small quantities of crude oil had been stored underground in the United States before 1975.

An early key decision made in developing the SPR was to use existing salt caverns wherever possible and to develop new salt caverns as required. This decision was based on the knowledge that there were more than 350 usable underground salt structures (domes) within a 50,000-square-mile area along the Gulf Coast of the United States, and that this area had additional advantages in terms of proximity to oil refineries, oil pipelines, and oil tanker port facilities. In addition, the technology for leaching storage caverns in salt was available.

Experiences of other countries with underground storage of crude oil. In 1916, a German firm obtained a patent for the use of solution-mined salt cavities to store crude oil and distillates. Nevertheless, no significant crude oil storage took place in Germany prior to 1972. In the 1970's, Germany and other foreign countries developed a considerable amount of underground storage. At the time the SPR program was initiated, major petroleum storage projects were under way in Germany, France, South Africa, and several other countries (*9*).

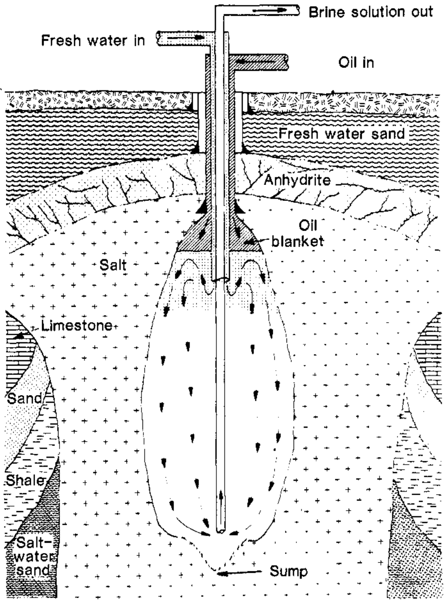

Fig. 1. Leaching a salt cavern.

The largest known foreign crude oil storage reserve was in Germany, where capacity in excess of 50 MMB had been developed in salt dome caverns. France had developed a 32-MMB diesel fuel storage facility in an abandoned iron ore mine and was developing approximately 50 MMB of crude oil storage in underground salt caverns. South Africa had also developed significant quantities of storage in abandoned coal mines, but the exact amounts were not published. Scandinavian countries were storing large amounts of refined products as well as crude oil in underground igneous rock caverns; their total crude oil reserves were estimated at 30 MMB (*9*).

Engineering Challenges

When the effort to develop the SPR was initiated in late 1975 and the use of salt domes had been selected, the engineering challenges were clear. Some of them are outlined in the following paragraphs.

Technology of large salt caverns. By 1975, the capacities of individual caverns developed in salt for storage of crude oil or petroleum products were at most 4 MMB; the majority were less than 1 MMB. A 1-billion-barrel strategic reserve based on 4-MMB storage caverns would require 250 caverns—and significantly more time and expense to develop than were desired. The SPR acquired several larger caverns, ranging from 6 to 17 MMB, and one of about 30 MMB, which had been developed by the chemical industry to produce brine as a feedstock for petrochemical manufacturing plants. LOOP storage facility mentioned earlier will have individual storage caverns of only 4 MMB, but LOOP's storage goal is only 32 MMB.

One of the engineering tasks of the SPR was to convert some of these existing large caverns to crude oil storage caverns for the SPR—specifically, to establish testing and certification procedures for these large caverns, which were not developed for crude oil storage. A second engineering task was to determine the most effective and efficient methods of rapidly developing new caverns with capacities on the order of 10 MMB.

Facilities for fill and drawdown and brine disposal. The logistics of withdrawing crude oil from storage and introducing it into commercial distribution systems at rates of 4 to 5 MMB per day presented another significant engineering challenge. Filling storage caverns presented a similar but easier task, because the required flow rates were significantly lower and principally involved reversing the flow in the facilities to be used for drawdown.

An extremely difficult problem confronting SPR development, however, was the disposal of the large quantities of displaced brine which result from the solution-mining (leaching) process. Typically, brine produced in industrial leaching of salt caverns has been disposed of by injecting it into subsurface aquifers, pumping it into holding ponds, or using it as feedstock for petrochemical plants. The subsurface injection rates acceptable to industry, generally on the order of 15,000 barrels per day per well, were far less than that required by the SPR system. The cavern development schedule for the SPR's billion barrels of storage anticipated brine disposal rates totaling over 1 MMB a day. Since about 8 barrels of brine are produced for each barrel of storage created, about 8 billion barrels of brine would be created to develop the SPR. The challenges in terms of potential environmental impact and the actual engineering required were significant and involved the development of major pipelines, large numbers of injection wells, and disposal facilities in the Gulf of Mexico. A similar but less complex problem was the need to develop access to large quantities of fresh water for leaching the caverns and for displacing the stored oil when necessary.

Geology of Salt Domes and Oil Storage in Salt

Geology of salt domes. As a storage medium for crude oil and petroleum products, rock salt is unsurpassed by any other naturally occurring rock because it is neither porous nor permeable, it is easily excavated by conventional mining techniques or by leaching, and it does not contaminate the stored crude oil or petroleum product.

The United States has vast deposits of bedded salt ranging from less than 1 meter to more than 300 meters in thickness and occurring at depths of a few meters to more than 6000 meters (*7*). Some of these salt strata have been deformed into unique structures called salt domes. The rock composition is essentially pure sodium chloride (halite) with minor amounts (5 percent) of calcium sulfate (anhydrite) and of other materials.

A salt dome is a massive and continuous column of rock salt that originated from a thick salt bed several thousand meters below the earth's surface. In the Gulf Coast region of the United States this "mother salt bed," deposited about 200 million years ago, is known as the Louann Salt (*10*). It is the salt domes, rather than the bedded salt deposits, that are of primary interest for the SPR.

Figure 1 is a cross section of a typical salt dome in the Gulf Coast region. It is a relatively circular or elliptical plug, occasionally with irregular spines projecting upward from the main salt mass. The top of the dome ranges in diameter from 0.8 to about 7 kilometers (the average is 3 kilometers in the Gulf Coast region), and the dome has a maximum diameter occasionally exceeding 16 kilometers. The surface of the dome is slightly convex upward, and an overhang (mushroom shape) is not uncommon. The modern concept of the evolution of salt domes postulates that plastic flowing salt has slowly moved upward through overlying sediments in response to density differences between the salt and the surrounding sediments (*10*). Similar salt dome structures occur throughout the world.

Effects of long-term storage of crude oil in salt caverns. There is no evidence that crude oils or refined products are contaminated by storage in a salt medium. Further, adsorption on the walls of a salt cavern or mine is negligible, and withdrawal operations—in the case of solution mines, which involve injection of water into the cavern beneath the oil—will cause some additional salt to be dissolved from the walls, freeing the adsorbed oil.

Potential loss of crude oil in salt cavern storage may occur because of the formation of a viscous layer, containing appreciable quantities of water, sediment, and salt and relatively enriched in trace metals and the acidic components of crude oil, that develops at the oil/brine interface in solution-mined salt caverns. On the basis of direct sampling and sonar surveys of several German caverns, this viscous layer is estimated to comprise a maximum of 0.5 percent of the volume of crude stored in a salt cavern (*4*). However, even the oil in this viscous layer is recoverable, as the Germans have demonstrated, by completely emptying a cavern and refilling it with a refined product. The viscous layer apparently develops over a long period of time, but at a decreasing rate as the sediment, water, and salt settle out.

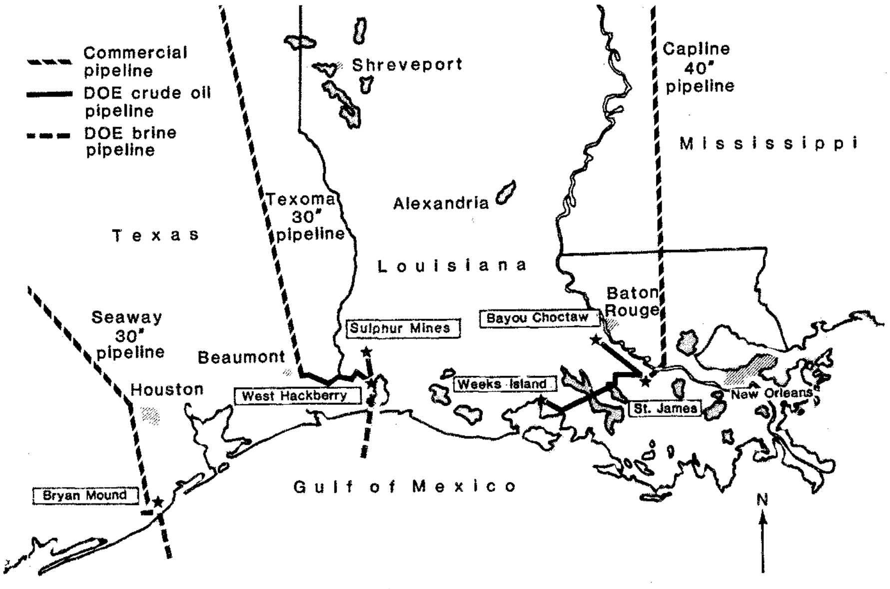

Fig. 2. Geographic location of the SPR system.

The question of long-term stability of crude oil stored underground arose early in the SPR program. Rather than attempt to simulate long-term oil storage in the laboratory, a study was undertaken of salt dome facilities in Germany where crude oil has been stored undisturbed for up to 6 years (*4*). Many of the individual storage caverns in Germany contained several different types of crude oil of known composition, which had been injected over a period of several months or years. One hypothesis being tested was that these different crude types would remain stratified after months or years of undisturbed storage, with lighter fractions overlying heavier fractions or lighter fractions preceding heavier fractions when the oil was withdrawn for refining. Representative undisturbed samples were therefore collected and analyzed. The results of these analyses indicated that total mixing had taken place within as little as 2 to 3 years of storage. The mixing is apparently caused by thermal convection. In all cases, the crude oil had not undergone any deleterious changes in quality.

In summary, long-term storage—up to 6 years at least for crude oil and 3 years for distillates—results in no deleterious changes in quality which would prevent the crude from being refined, or used directly as with distillates, by existing technology (*4*).

Site identification and selection. In 1975, the Federal Energy Administration began to identify site locations for underground petroleum storage. After 300 salt domes and numerous conventional mines were screened and evaluated, the number of potential sites for initiation of the storage program was reduced to approximately 20. These 20 sites were chosen because they best met established selection criteria, such as location with respect to major ports and distribution pipelines (*2*).

Existing solution-mined caverns, developed by industry, were identified as potential crude oil storage caverns at the Bryan Mound salt dome in Texas and at three salt domes in Louisiana: West Hackberry, Bayou Choctaw, and Sulphur Mines. In addition, one conventionally mined salt mine at the Weeks Island salt dome in Louisiana was chosen (see cover photo and Fig. 2). Conversion of these existing caverns constituted phase 1 of the development of the SPR, with a storage capacity of 248 MMB. The development of 29 new caverns at the phase 1 sites constitutes phase 2 of the

SPR, and will add another 290 MMB. Phase 3, to add 210 MMB, will consist of the development of a new site and additional expansion of two phase 1 sites. Phase 4 is at the stage of concept formulation (*3*).

Fill and drawdown operations. Each SPR site is connected to a marine terminal and a major interstate pipeline for distribution of the oil during a drawdown. In addition, the Department of Energy (DOE) constructed a new marine terminal at St. James, Louisiana, to support the Bayou Choctaw and Weeks Island storage facilities. The St. James facility provides for connection to the Capline pipeline distribution system and to marine transportation. More than 266 kilometers of large pipelines (91.4 to 106.6 centimeters in diameter) were constructed to connect the storage sites with these terminals.

Filling the Strategic Petroleum Reserve. Filling the SPR involved purchase, ocean transportation, and injection of crude oil into the storage caverns and disposal of brine displaced by the oil. It commenced in July 1977, 4 months after the SPR plan (*2*) became effective, and continued until August 1979, when tight market conditions curtailed the filling. At that time the SPR had an inventory of 91.2 MMB. Filling resumed in September 1980, with the equivalent of 100,000 barrels per day of Naval Petroleum Reserve (NPR) crude oil, or oil exchanged for NPR crude, being delivered to the SPR. At present, the SPR has the capability to fill at an average rate of more than 500,000 barrels per day. Figure 3 illustrates the fluid flow at a typical SPR storage site.

Drawing down the Strategic Petroleum Reserve. During drawdown, oil is displaced from a cavern by injecting fresh water beneath the oil. At Weeks Island, 11 submersible pumps will lift the oil from the salt mine (*3*). Oil is pumped from all the storage sites through pipelines to terminals for distribution to interstate pipelines, local refineries, or waterborne transportation to other regions of the United States.

Permanent drawdown systems were operational at three sites (Bryan Mound, West Hackberry, and Bayou Choctaw) by September 1979. These systems are capable of providing crude oil to the petroleum industry at a rate of 1 MMB per day. In February 1980, the Secretary of Energy initiated a surprise exercise which required 600,000 barrels to be withdrawn from the West Hackberry storage site, to test the SPR's capability. Site equipment operated satisfactorily during this exercise and all performance objectives were met or exceeded. In April 1980, a planned drawdown exercise was conducted at the three operational sites. Approximately 1.4 MMB was withdrawn at an average rate of 1.2 MMB per day, 25 percent above the design rate.

Development of new solution-mined caverns. Twenty-eight new salt caverns, each with a capacity of 10 MMB, are being developed for storage of oil through leaching. This will result in an SPR storage capacity of 500 MMB by the end of 1986.

Leaching begins with a cavern design and a plan which takes into account the size and shape of the dome and the quality of the salt. Major design parameters are cavern size, shape, and separation; the initial cavern separation provides for cavern growth (resulting from cycling the crude oil) and salt creep while maintaining structural stability. Operations begin with drilling wells into the salt. The wells are lined with steel casing that begins at the surface, runs through the overlying sediments and cap rock, and extends into the salt. This casing is cemented into the cap rock, forming a tight bond; the bottom end of the cemented casing is referred to as the casing seat. The well is drilled to a depth of approximately 700 meters below the casing seat (Fig. 1).

The cavern is leached by inserting two concentric suspended strings of pipe inside the cemented casing and then injecting water into the cavern and displacing brine out of it through these pipe strings. Approximately 80 to 90 MMB of water must be circulated through the salt formation to develop a single 10-MMB cavern. This process takes approximately 990 days, and several caverns are developed simultaneously, with oil being injected long before the cavern's full volume is reached. Including the sump, the actual volume of a 10-MMB rated cavern is more than 12 MMB.

Disposing of salt brine in the Gulf of Mexico. The leaching of salt caverns and filling of SPR storage facilities with oil

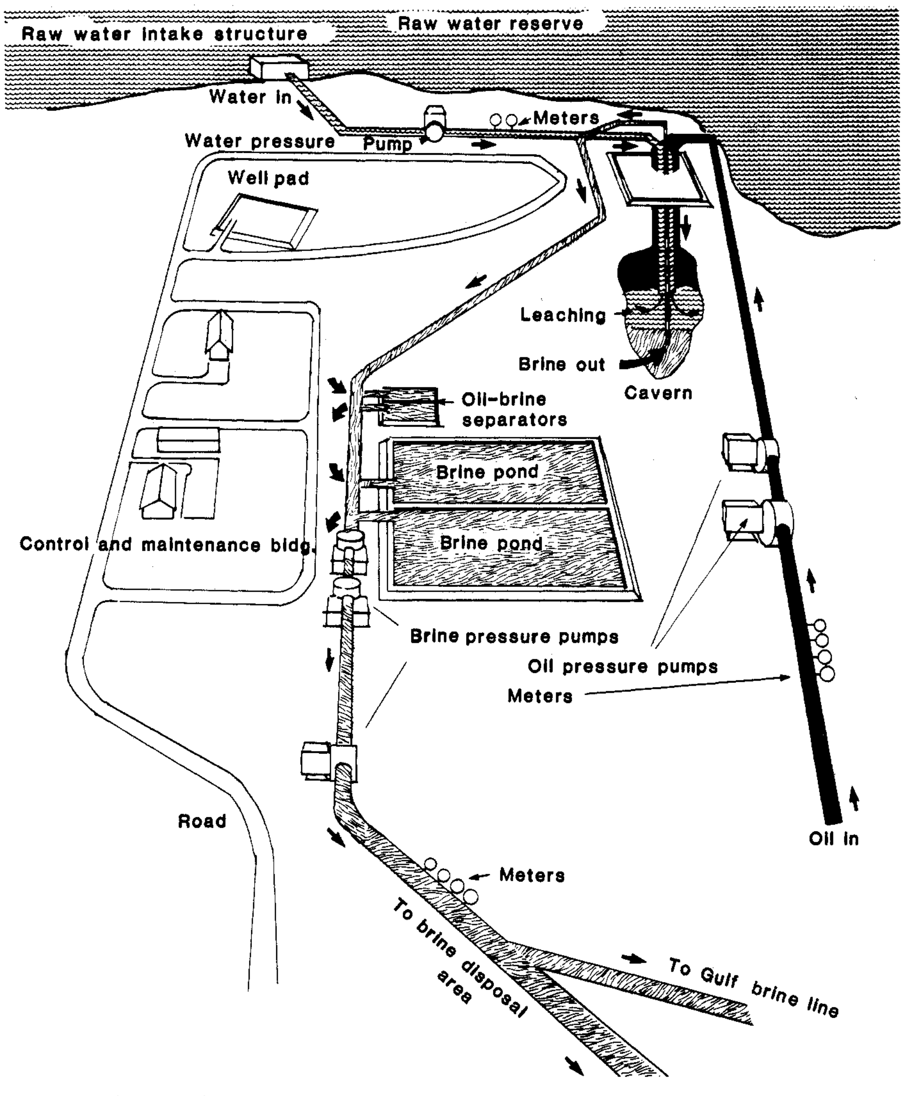

Fig. 3. Fluid flow leaching and filling process at a typical salt cavern site.

will require disposal of concentrated brine at average rates of 680,000 barrels per day at Bryan Mound and 1 MMB per day at West Hackberry for a period of 6 to 7 years. Exhaustive studies concluded that the only workable means of disposal was diffusion into the ocean (specifically the Gulf of Mexico), similar to the German practice of brine disposal in the North Sea.

Preliminary investigations, begun in 1976, indicated that discharge of brine to the Gulf without significant environmental impact was technologically feasible (*11*). Subsequently, a 0.9-meter brine pipeline was constructed at Bryan Mound to a diffuser location 20 kilometers offshore. A 0.9-meter offshore brine pipeline is currently under construction at West Hackberry. Since the beginning of brine discharge at Bryan Mound in March 1980, environmental problems have not materialized.

Discharge of brine into the Gulf of Mexico required a wastewater discharge permit from the Environmental Protection Agency (EPA). When the discharge permit for Bryan Mound was applied for in April 1977, EPA ocean discharge guidelines did not exist. The nature and scale of the proposed discharge were unprecedented in this country, and the regulatory procedure for handling it was not in place. Since the National Oceanic and Atmospheric Administration (NOAA), as well as EPA, has responsibility for oceanic environmental issues, SPR joined with NOAA in an effort to address ocean brine disposal problems (*12*). This has gradually evolved into a major federal ocean program in direct response to concerns expressed by federal and state interests and by special interest groups. The initial tasks were to survey the existing data for Texas and Louisiana nearshore waters and to develop and apply a numerical model for predicting brine plume dispersion. NOAA asked Parson's Laboratory at the Massachusetts Institute of Technology to perform the latter tasks.

Conclusion

Storage space for the SPR is currently being developed in new caverns by leaching at rates three to four times higher than any previously employed. This has been made possible through the development of techniques for disposing of unprecedented quantities of brine by diffusion into the Gulf of Mexico.

The total cost of the 750-MMB reserve is estimated at $39.5 billion. Approximately 92 percent of this cost is for acquisition and transportation of crude oil. The initial 90 MMB of oil in the reserve were purchased at an average cost of $14.33 per barrel. Because of inflation and real growth in oil prices, this crude oil is worth approximately $3.25 billion at current world market prices—an appreciation of $2 billion. The cost of developing storage facilities has averaged approximately $3.50 per barrel of capacity in 1981 dollars.

The accomplishments of the SPR program in the 6 years since it was created are unprecedented anywhere in the world. The present SPR oil inventory of more than 100 MMB represents the largest government-owned storage reserve in the world, with almost twice the capacity of the next largest reserve. Thus the SPR already goes a long way toward reducing U.S. vulnerability to oil supply disruptions.

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