SOLUTION MINING
RESEARCH INSTITUTE

812 MURIEL STREET
WOODSTOCK, ILLINOIS 60098
815-338-8579

MEETING
PAPER

REVIEW OF U.S. STRATEGIC PETROLEUM RESERVE PROGRAM

BY:

CHARLES W. QUERIO,

MARK ERIK STEINER

and

WILLIAM E. DURNELL,

PB-KBB INC.

Manchester, UK
October 1982

SPE 10167

EXPANSION OF SOLUTION CAVERN STORAGE TECHNOLOGY

By:
CHARLES W. QUERIO,
MARK ERIK STEINER
and
WILLIAM E. DURNELL,
PB-KBB INC.

This paper was presented at the 56th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, held in San Antonio, Texas, October 5-7, 1981.

EXPANSION OF SOLUTION CAVERN STORAGE TECHNOLOGY

ABSTRACT

The U.S. Strategic Petroleum Reserve being created along the Gulf Coast will provide the largest inventory of crude oil of any nation in the world. Unique engineering has been employed to solve the problems presented in creating large volume underground caverns rapidly and for handling the high flow rates required during oil withdrawal. This paper discusses the design considerations (criteria), development schedules and methods used to meet the objectives of the program.

INTRODUCTION

Americans are accustomed to being in lines. To enter stadiums and theaters, to pay for purchases at retail establishments, or to view memorabilia at historic sites. However, during the winter of 1973-74, we were forced into new, unwelcome lines. Those waiting to buy gasoline.

Caused by an embargo by the major oil exporting nations, these severe petroleum supply disruptions served as a vivid reminder of America's dependence on imported oil. Our nation's demand for foreign petroleum has tripled during the last three decades--from about 15% of our total demand in 1950, to almost 45% in 1980. Despite the current glut of petroleum, future embargoes or other interruptions could still have severe effects on our economy.

This paper describes the unique engineering solutions to problems associated with leaching large-volume underground storage caverns for crude oil. To handle the high flow rates associated with accelerated development of these caverns, up to three wells must be drilled for each cavern. An alternative method calls for 20-inch diameter final casings, which are about twice the size used in conventional oil and gas drilling. Design considerations affecting the caverns are discussed, and possible additional applications for the technology are included.

BACKGROUND AND OBJECTIVES

To make us less dependent on overseas petroleum sources, the United States Congress passed, in December 1975, the Energy Policy and Conservation Act (EPCA). This act gave the requirements of a Strategic Petroleum Reserve (SPR) of up to one billion bbls. of crude oil. The SPR Plan set an intermediate goal for early storage in the Gulf Coast by the end of 1980, and one billion bbls. of oil in storage by 1985. The Department of Energy (DOE) is charged with the overall responsibility for SPR, while the project has involved many other organizations.

The first major questions arising from the SPR Plan were how and where to store one billion barrels of oil. Numerous storage possibilities were considered.

Examples were:

1. Aboveground tanks
2. Mothballed ships
3. Conventional mines
4. Salt caverns.

Secondly, the storage sites had to be located for efficient pipeline and tanker access, to permit fast removal and distribution, in the event of oil supply disruption.

After many studies and careful consideration, a decision was made to store the reserve in solution and conventionally mined caverns in underground salt dome formations along the Gulf Coast. Several excellent reasons accounted for this choice. The caverns offered:

1. Considerable existing capacity and the potential to develop additional storage capacities at selected sites.
2. Stable and safe storage.
3. Storage costs ranging from approximately 1/3 to 1/6 the per barrel cost of aboveground storage depending upon total volume and support facilities.

In addition, the caverns are near both port receiving facilities along the Gulf Coast--where two-thirds of overseas oil coming into the U.S. now enters--and major crude oil refining and distribution centers.

In 1977, the DOE acquired sites on five salt domes (Figure 1, Page 18). Bryan Mound at Freeport, Texas, to serve the Seaway pipeline; West Hackberry and Sulphur Mines, near Lake Charles, Louisiana, to serve the Texoma pipeline originating from Nederland, Texas; Bayou Choctaw near Baton Rouge, Louisiana area and Weeks Island near Lafayette, Louisiana to serve the Capline pipeline at St. James, Louisiana. The sites offered a combined existing capacity of about 250 MMB. Salt domes with existing storage capacity were chosen to permit development in a relatively short time. Additional new caverns would be developed by leach/fill methods.

The use of existing solution mined caverns and the development of additional oil storage space presented unusual problems that required innovative solutions. Never before had such large caverns been used for storage purposes. Methods of analyzing and testing these caverns to verify the ability to contain oil were required.

Developing new caverns in an efficient yet expedient and safe manner required innovative engineering approaches.

This is the first time that large quantities of crude oil are being stored underground in the U.S. No nation has ever before undertaken a program of this magnitude, in terms of quantity of oil and time frame for development. While Germany and France have established strategic reserves in subsurface caverns, solution cavern capacity has been up to 3.3 MMB of oil, and the facilities have required up to 10 years to develop. Total volume of these facilities is about 100 MMB.

Cavern size is the unique feature of America's SPR Program. It requires 10 MMB storage caverns, which are about three times the size of any previously used elsewhere. This project also involved the utilization of raw water as the displacement media, therefore requiring the design to allow for cavern growth with every displacement.

PB-KBB Inc.'s involvement in the U.S. SPR Program began in July, 1977. The Department of Energy (DOE) contracted with the PB-KBB Inc. family of companies for the detailed design of the solution mined cavern facilities to be included in the program. The design included all surface facilities (buildings, instrumentation and control, pipelines, etc.) as well as subsurface systems. In January 1979, we were awarded another DOE contract to perform design, analysis and support services for new sites to be entered into the SPR Program. This involvement has continued to the present.

UNDERGROUND SALT DOMES

Created by geologic processes spanning millions of years, salt domes are large underground salt formations. About 200 million years ago, the Gulf of Mexico was a closed salt water basin. A precipitate was formed, which is now the original salt bed. Geologists call this the Mother Salt (Louann). Approximately 60 million years ago, sediments flowed into this basin, from the North American continent, and were deposited above the salt bed. By 30 million years ago (Figure 2, Page 19), the weight of the accumulated sediments had reached the point where downward pressure on the salt caused the less-dense salt to deform and flow upward toward the surface. As the salt passed up through the overlying sediments, long, finger-like projections--called salt domes--developed. When a buoyant equilibrium was reached between the salt and the sediments, the salt eventually stopped moving upward (Figure 3, Page 20).

Salt domes are analogous to fingerprints, in that no two are exactly alike (Figure 4, Page 21). The domes vary in both size and shape. Most authorities agree that a strict classification according to size and shape is not feasible. As a result, most listings of Gulf Coast domes are made according to the location (interior, coastal and offshore), and depth to the salt. The latter are classified as shallow (0-4,000 ft.), intermediate (4,000-10,000 ft.) and deep (below 10,000 ft.). Some terms used to define or better describe individual salt domes include cone-shaped, elongate, inclined, mushroomed, oval, overhanging, round, spinose, table-topped and vertical.

There are more than 500 known salt domes in the Gulf Coast states and offshore area of the United States. Gulf Coast salt domes were the birthplace of the Frasch sulphur industry, and the location of the first oil gushers that ushered in the modern liquid fuel age. In addition, Gulf Coast salt domes are used for the underground storage of LPG.

The existing caverns in salt domes, that are now being filled in the SPR program, were developed as the result of brining operations for the salt and chemical industries. They are normally irregular in shape, and vary in size. Some of these caverns could hold structures like the Empire State Building, with room to spare.

STORAGE SITES AND PIPELINES

Let's take a closer look at each of the storage sites. Oil is being stored in five (5) existing caverns at the West Hackberry site near Lake Charles, Louisiana. The 450-acre site contains the world's largest salt dome. Some sixteen (16) new caverns, each with a 10 MMB capacity, are to be leached here.

Raw water for leaching and oil displacement will travel through an intake structure in the Intercoastal Waterway. Injection pumps, operating at a design rate of more than 1 MMBPD, will support leaching. Brine will be pumped from the site to 12 miles offshore, into the Gulf of Mexico.

Oil will travel to the site through a 42-inch pipeline from the SUNOCO terminal in Nederland, Texas, some 42 miles away. West Hackberry is designed for oil withdrawals at a 1.4 MMBPD rate to the Texoma pipeline.

Also located near Lake Charles, Louisiana, the Sulphur Mines site is where the Frasch Process for mining sulphur was commercially perfected by 1912. The site offers five (5) existing caverns for crude oil storage. Oil stored here will be withdrawn into the Texoma pipeline.

Located near Freeport, Texas, Bryan Mound gets its name from the fact that the underlying salt dome has pushed the site 15 feet above the surrounding wetlands. Oil is being stored in four (4) of the five (5) existing caverns, with a total capacity of 60 MMB. The site will have an additional storage capacity of 120 MMB when twelve (12) planned new caverns, each capable of holding 10 MMB, are leached.

Raw water for leaching is being drawn from the Brazos River. Disposal pumps will push the brine through a new 36-inch pipeline that discharges 12 miles offshore into the Gulf of Mexico.

A DOE 30-inch pipeline has been built from berthing facilities at Freeport, 5 miles away, to Bryan Mound, and from there to the Seaway Jones Creek Tank Farm. Four tanks there provide surge capacity. Raw water, injected into the caverns, will displace oil to the surface. The system will be capable of withdrawing at a rate of 1 MMBPD.

Located in a swampy forest near Baton Rouge, Louisiana, facilities at Bayou Choctaw are now complete for storing 36 MMB. Oil is being stored in four (4) of fourteen (14) existing caverns considered suitable for storage after testing. Four (4) new ones, each with a 10 MMB capacity, will be developed.

A raw water intake structure, housed at Cavern Lake on the site, provides water for leaching. Brine will be pumped to eleven (11) nearby brine disposal wells.

All the sites previously discussed contained existing solution-mined caverns, created over the last 40 years, by solution mining the salt for industrial uses. On the other hand, Weeks Island Storage Facility, was a conventional, operating rock salt mine.

Surface facilities were built and the subsurface rooms and tunnels were converted to facilitate flow and reduce trapping for the storage of 75 MMB of oil. All incoming oil will flow directly into the cavern's two levels, and will be displaced through the use of submersible pumps.

ENGINEERING CONCEPTS

While existing caverns were being tested and prepared to receive crude oil, plans were being made for the controlled leaching of new caverns for optimum size and shape, expressly for storing crude oil. This optimization considered overall cost and schedule as well as stability and ability to retrieve stored oil. It takes about 3.5 years to leach a new 10 MMB cavern.

First, the salt dome is studied. Salt core samples and other data are analyzed to determine the size, location and characteristics of the salt, the non-salt impurities within it, and the materials above the salt. Computer analyses of this information guides the cavern's development. Caverns are designed to provide maximum storage capacity at each site, within the required depth. Spacing between caverns is maintained to assure geotechnical stability. Cavern spacing arrangements must consider cavern growth during the predetermined maximum withdrawal and refill cycles, utilizing the water. Physical and regulatory restrictions on brine disposal rates had to be accomodated. Brine produced during leaching and during oil fill activities will pass through brine/oil separators, and then to holding ponds.

CAVERN DESIGN

New SPR caverns are constructed to a somewhat standardized configuration. Depth and salt quality are the major differences between caverns. Depth is dictated by the geology of the individual sites. State regulations also require some modification of the well construction and drilling program.

The basic SPR designs for new caverns took into consideration DOE planning guides and previously developed structural considerations. The caverns are to be constructed (by leaching) to a 2000 foot high "flower pot" shape, with diameters of 230 feet at the top, and 170 feet at the bottom. This shape allows for the continued leaching, during oil displacement with raw water.

Cavern design for leaching was based on calculations using a three-dimensional model, considering non-homogeneous salt, for solution mining simulation (Figure 5, Page 22).

The model* simulates the leaching process and predicts the following criteria from the beginning to the end of the leaching period:

.. Cavern Configuration
.. Daily Rate of Volume Creation
.. Gross Cavern Volume
.. Net Volume Creation
.. Residue Volume
.. Depth to Residue Bed
.. Volume of Hydrocarbon Blanket
.. Bottom of Hydrocarbon Blanket

* Owned by PB-KBB Inc. family of companies, the unit is the only such model known to exist.

Input data for the model are:

- .. Salt Properties and Components
- .. Volume Fraction of Insolubles
- .. Depth of Boreholes
- .. Location of the Suspended Leaching Strings at various Time Steps
- .. Flow Direction -- Direct or Indirect
- .. Blanket Depth or Oil Injection and Withdrawal Flow Rates
- .. Raw Water Injection Rate.

A unique feature of the model is its history matching capability that allows for adjustments to future predictions, based upon inputs from actual results.

Before the project began, the exact properties of the salt underlying the sites were unknown, and analyses was based upon leaching in homogeneous salt. The existing model setup actually allows for salt core (if available) to be analyzed, and data fed directly into appropriate data banks.

Injected raw water's salinity was assumed to be from 0-36 grams/liter, to match the salinity of fresh and sea water, respectively.

The major design criteria covering caverns made by the leach/fill process are cavern stability, system hydraulics and salt leaching rate. Stability is of prime concern. An arched stress pattern builds up in the salt above the cavern roof, as salt is extracted from the dome by leaching. Thus, enough salt above the cavern roof must be left to allow for safe distribution of the stress that develops with the cavern's formation. Limitations on cavern depth include economics (power costs) and salt's creep behavior, both of which increase with depth. The SPR Caverns are not designed for depths to exceed 6,000 feet to control creep and cavern closure.

Two ratios were used to evaluate the relative stability of these large caverns. The S/D ratio (Figure 6, Page 23), measures the salt roof thickness (S) to cavern diameter (D). Salt provides the majority of the caverns structural stability. Thus, the thicker the salt over the cavern relative to its roof span, the more stable the roof.

The P/D ratio is the second consideration used in evaluating cavern stability for numerous caverns efficiently located in the same salt mass. This ratio expresses the amount of salt remaining between the caverns, or the salt pillar (P), relative to cavern diameter (D). Since the overburden originally held up by the excavated salt must now be borne by the remaining pillar, the average pillar stress increases. The larger the pillars, the lower the pillar stress, and the decreasing tendency of the pillars to yield. The hydraulic pressure in the cavern partly balances this overburden stress.

Developing the proper ratios for cavern design and placement is a site specific task. The actual properties of the salt involved must be incorporated into the rock mechanic equations.

WELL PROGRAM

The wells used for the leach/fill caverns are designed to guarantee well integrity throughout the well's life, and to offer maximum protection against possible surface water pollution during the project's life.

Each site's casing program was designed to meet state regulations in the most economical manner. Casing sizes are developed based upon rig considerations, flow rate requirements, pressures and velocity restraints and operating criteria.

A conductor pipe driven about 80 feet deep, is the top-most casing. For protection from fluid migration between aquifiers, a protection string will be set into the caprock top and fully cemented to the surface. A casing cemented about 100 feet into the salt serves as an additional protective string. Finally, a production casing will be cemented approximately 600 feet into the salt, with cement returned to the surface.

Additional strings of casing will be needed at some sites, when the caprock is known to be poor. A larger conductor pipe and surface casing must be set to insure that the well is completed with appropriate casing to the needed depth.

Therefore, the well programs feature a minimum of two (2) fully cemented strings of casing into the salt. Before the cement shoe is drilled out, the integrity of each casing is checked by pressure testing. After each casing is cemented, logs are run to verify cementing.

After well pressure tightness tests are made, a pair of suspended strings are run for subsequent cavern leaching. To prevent undermining the casing seat and to prevent any uncontrolled leaching that may possibly result in pressure tightness loss, a hydrocarbon "blanket" is introduced and floating on the water/brine, cavern leaching is carefully controlled.

LEACH/FILL PROCEDURE

In order to meet DOE schedules for oil storage, careful consideration was given to the impact that such items as workovers for sonars and resetting leaching strings would have on the time table. Thus, the leach/fill procedure was developed to provide maximum oil storage rates, yet maintain safeguards controlling and monitoring the operation.

To create the caverns, one or more wells are drilled into the salt. Each is equipped with concentric casings for leaching process. Before leaching begins, an oil/brine interface is made at the planned roof elevation, to protect the cavern roof from leaching. Direct leaching is used, meaning the raw water is pumped down the inside casing, and the displaced brine flows to the surface through the outermost casing (Figure 7, Page 24). The leach/fill procedure occurs in five (5) major stages, with cavern depressurization and sonar surveys following each stage. Careful reviews determine the actual leached configuration, and adjustments are made to develop the cavern, as closely as possible, to the computerized design. While the cavern is being developed, the oil/brine interface depth is measured often to check cavern growth.

Sump development is the first major step (Figure 8, Page 25). A total volume of 1 MMB is required to hold the estimated 5% insoluble salt impurities that will drop to the bottom during cavern enlargement. This space must be created in advance, and once filled, cannot be counted as oil storage space. To protect the cavern roof from leaching, an oil/brine interface is established.

After the sump stage is completed, leaching is stopped and the cavern depressurized. The first of six cavern sonar surveys is then made. At this point, the gross cavern volume is approximately 1.4 MMB.

The next step is chimney leaching. The leaching strings are repositioned and the oil/brine interface is reset at the cavern roof. Using direct leaching, a chimney is created. The caverns are again depressurized, and a sonar survey is made. When the cavern volume reaches about 2.5 MMB, the chimneys are completed.

The next step is roof development. Leaching strings are repositioned, and the oil/brine interface is again established at the cavern roof. Direct leaching is continued. As the fresh water dissolves the salt, a water/brine-filled cavern begins to form in the salt dome. Oil injection and roof developments proceed in increments to give optimum control over the roof's shape. After each incremental volume is created, oil is injected to lower the oil/brine contact level.

Two sonar surveys are scheduled during roof development. The first offers early control of roof shape, and the second survey is made when roof development is completed. The cavern's approximate cumulative volume are 4.2 MMB after the third sonar survey, and 6.6 MMB when the roof is completed.

After the fourth sonar survey is completed, the leaching strings are repositioned and indirect leach/fill begins. By indirect leaching (Figure 9, Page 26), we mean the fresh water is pumped down the outermost casing and the displaced brine reaches the surface up through the innermost casing. Simultaneously with indirect leaching, oil is injected to fill the cavern's upper portion. Oil/brine interface is regularly monitored after oil injection. Cavern growth is controlled by varying the depth of water injection and brine withdrawal casings, or changing the rate or method of water injection.

When the cavern's net volume reaches about 9.4 MMB, the fifth sonar survey is made. The strings are set near each other for the final leach/fill stage, which continues until the net cavern volume reaches 11 MMB. Both leaching casings are removed and the sixth sonar survey is made to verify that the full cavern volume has been reached. A final oil fill is made to bring the storage total to 10 MMB. For every 10 MMB oil storage cavern, an additional volume of 1 MMB is designed in to compensate for cavern creep, and to provide a margin (Figure 10, Page 27). Thus, every 10 MMB oil storage facility needs an 11 MMB open cavern space.

After the cavern is leached, a suspended casing will be used to inject the displacement water into the cavern's bottom. This will result in the diameter at the bottom increasing more quickly, during cycling, than the top (Figure 11, Page 28). After five cycles, the caverns are planned to be uniform cylinders with a diameter of 270 feet, and a volume of 20 MMB.

Since this is a strategic reserve, cycling will occur only during a national emergency. Raw water rather than brine will be used to displace the oil. This will cause the cavern's diameter and volume to increase, the latter by about 15% for each complete cycle.

WORKOVER PROCEDURE

Special workover procedures with safety steps apply during well-adjustment and cavern surveys. Blow-out preventers or wireline lubricators are installed on the wellhead for the needed well maintenance and surveys. Equipment needed, such as lubricators, blowout preventers and shears, varies according to the required service or adjustment.

SUMMARY

The Strategic Petroleum Reserve represents the first large-scale use of the Gulf Coast salt caverns for Crude Oil Storage. Design of a storage cavern development program involved state-of-the-art applications for:

1. Cavern size.
2. Placement of numerous caverns in a confined area.
3. Accelerated cavern development while allowing for early storage.
4. Large volume brine disposal.
5. Displacement of large storage volumes with raw water.
6. Testing and conversion of large existing caverns to storage.
7. Supply of large volumes of raw water.
8. Working with restricted budgets and continuous regulatory observation.
9. High rates of flow for oil, water and brine.

Considerations requiring design attention for the leach/fill method include cavern stability, system hydraulics and the salt leaching rate. Enough salt must be left above the cavern roof to safely distribute stresses developing with the cavern's configuration. Creep formation and power costs, which increase with depth, limit cavern depth. To control creep and cavern closure, SPR caverns are designed to a 6,000 ft. maximum depth.

Ratios of salt roof thickness to cavern diameter, and between the salt pillar relative to cavern diameter, are used to gauge relative cavern stability. Salt leaching rates are among the factors considered in developing procedures to meet DOE timetables for oil storage.

The safety and stability of solution caverns developed in salt domes combined with their location, present opportunities for unique and specific applications. Such uses include storing solid hazardous toxic wastes, liquid products including hydrocarbons, raw, refined and intermediate fuel stocks and compressed air for peak power shaving. The state-of-the-art allows for the flexibility of salt caverns as storage containers to be totally utilized.

REFERENCES

1. Hawkins, M. E. and Jirik, C. J., "Salt Domes in Texas, Louisiana, Mississippi, Alabama, And Offshore Tidelands: A Survey", U. S. Department Of The Interior, Bureau of Mines, Information Circular 8313, (1966), p.5.

PB-KBB Inc.
Subsurface Systems & Technology
HOUSTON, TEXAS

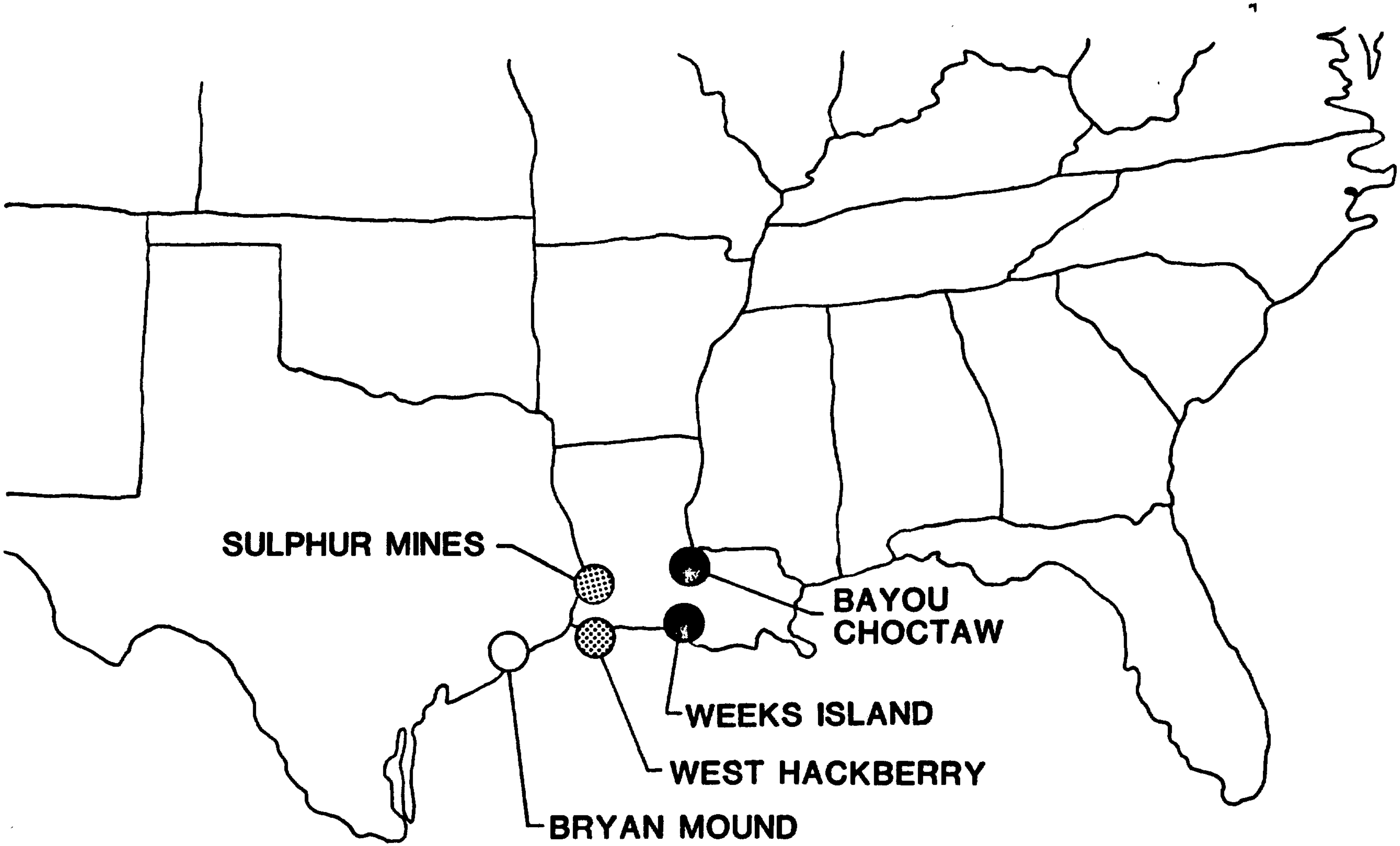

Fig. 1–Gulf Coast SPR storage sites.

End of Mid-Tertiary--30 Million Years Ago

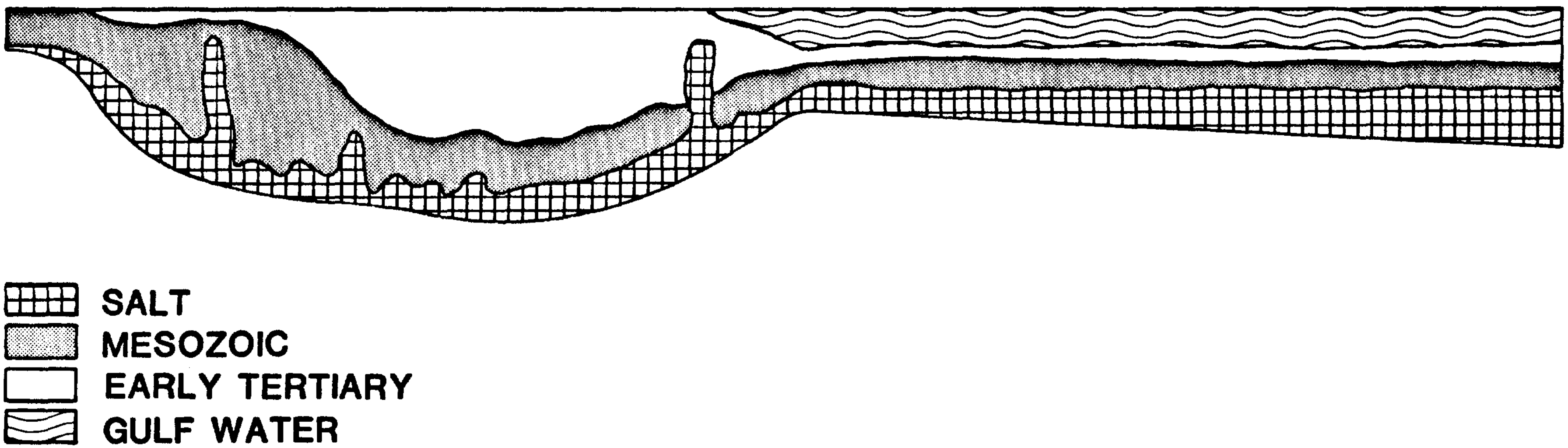

Fig. 2–Sediment deposited above salt beds formed the Gulf of Mexico.

Formation of Salt Dome-Present Time

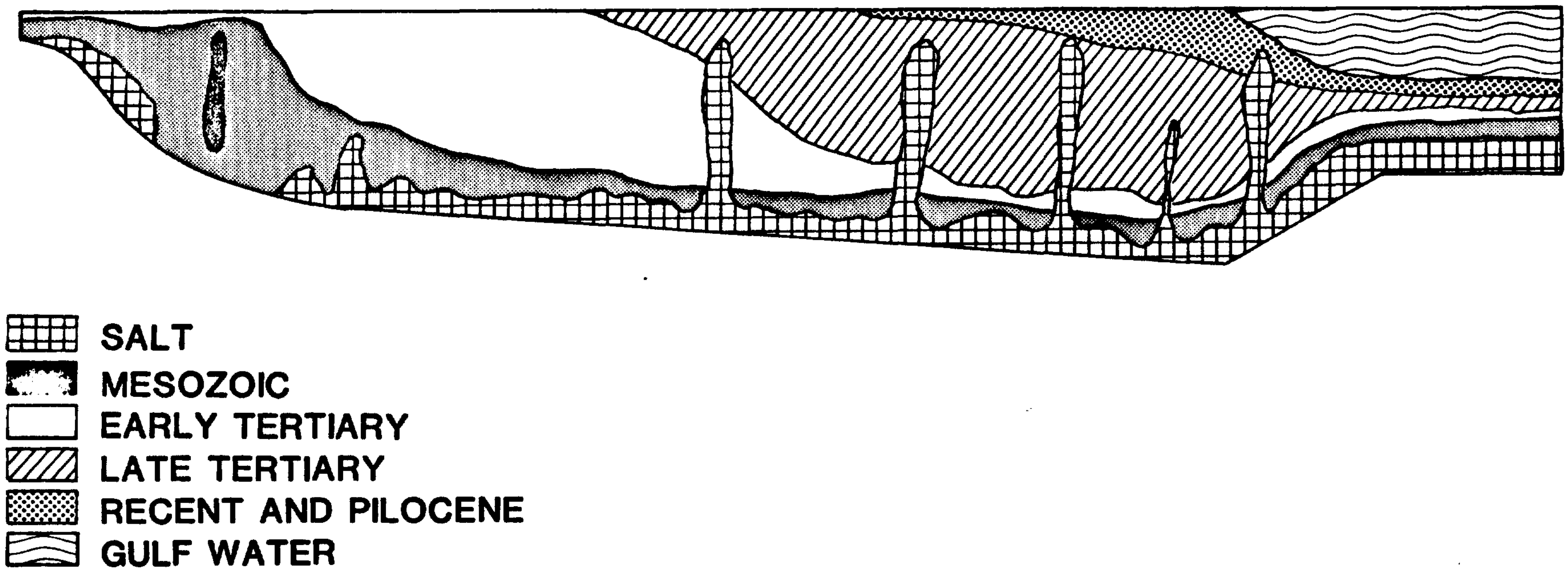

Fig. 3–Upward movement of projections formed salt domes.

Caverns in Salt Dome

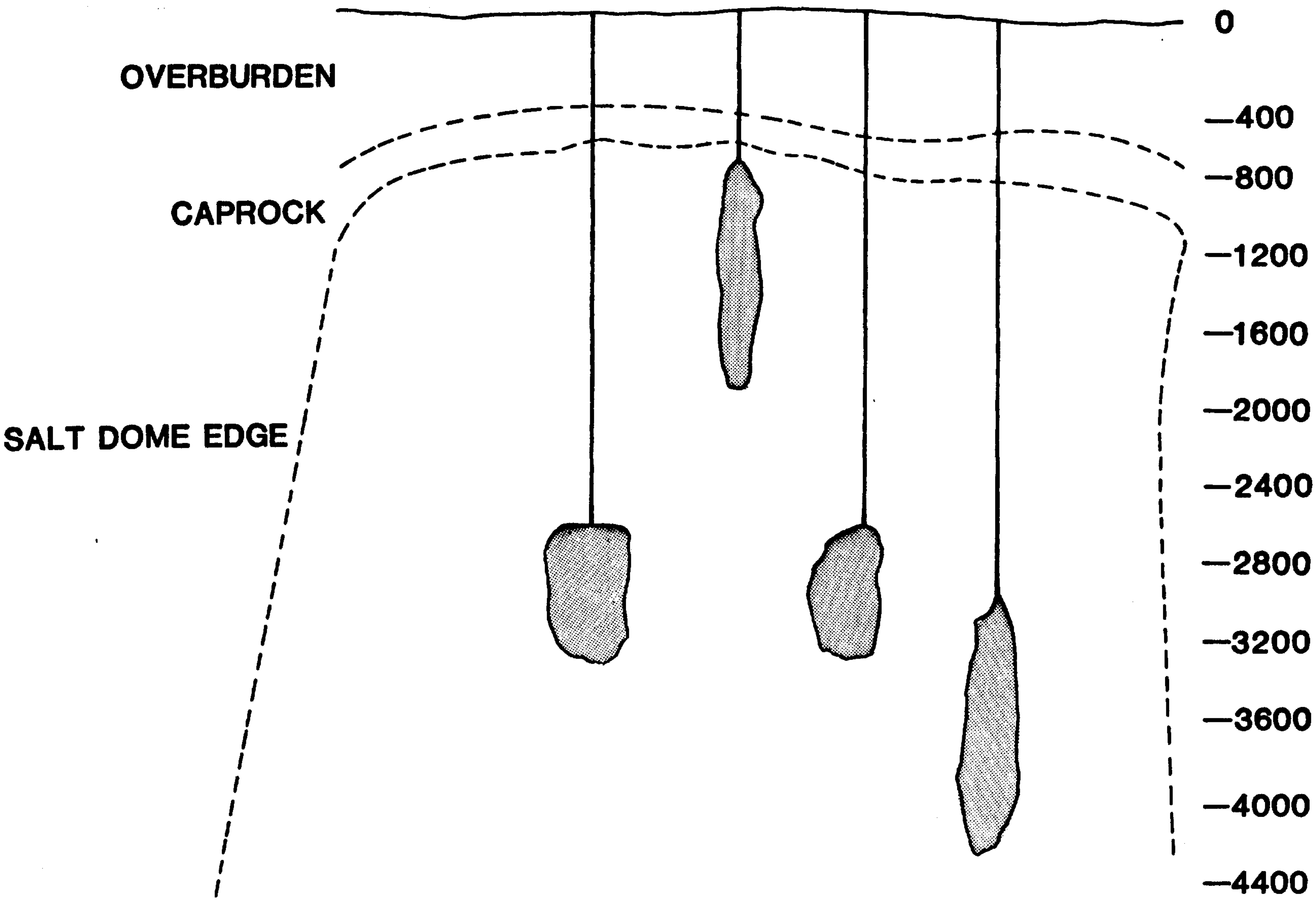

Fig. 4–The varied shapes of salt caverns.

SCALE IN FEET

PB-KBB Inc.
Subsurface Systems & Technology
HOUSTON, TEXAS

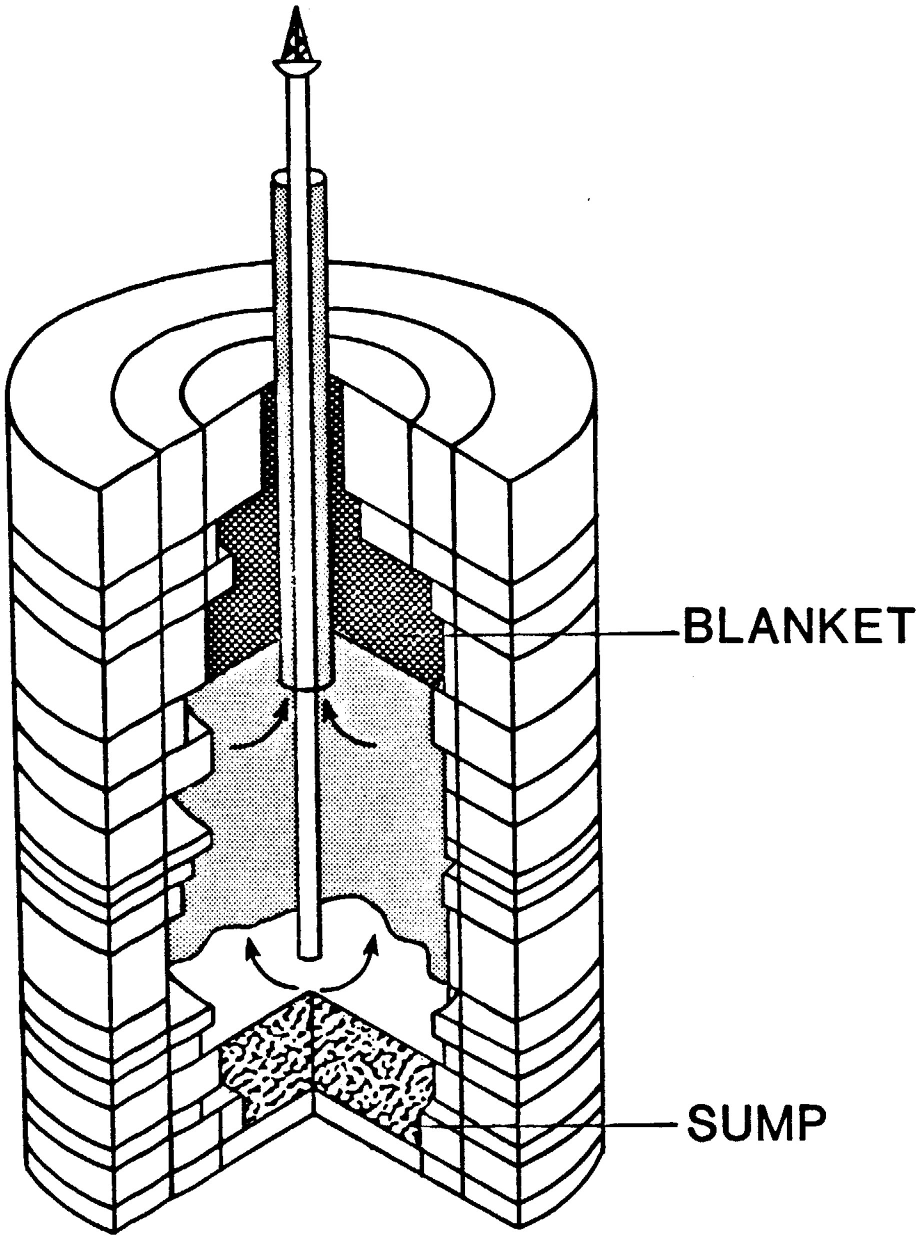

Fig. 5–Three dimensional simulation model.

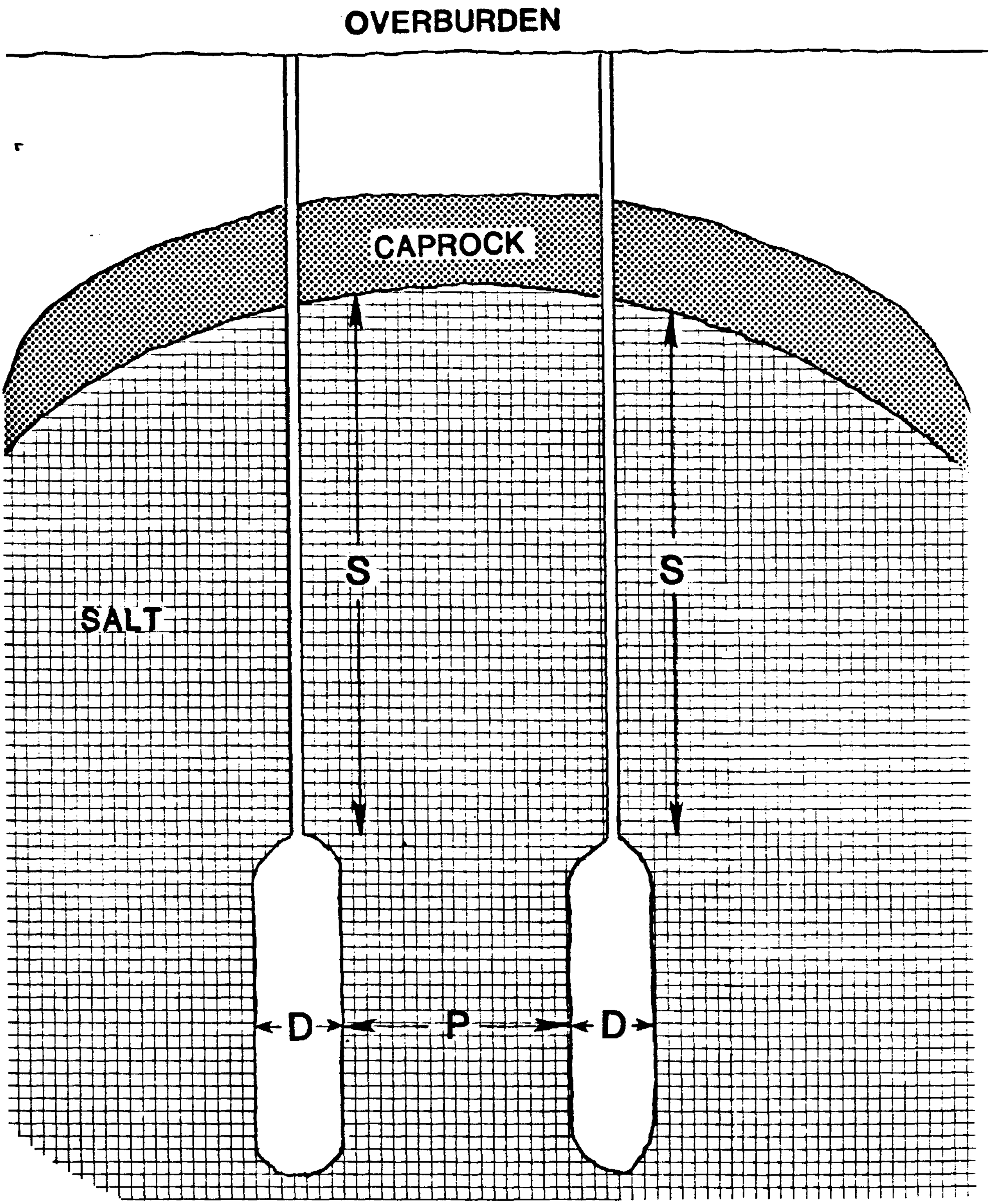

Fig. 6–Nomenclature for judging cavern stability.

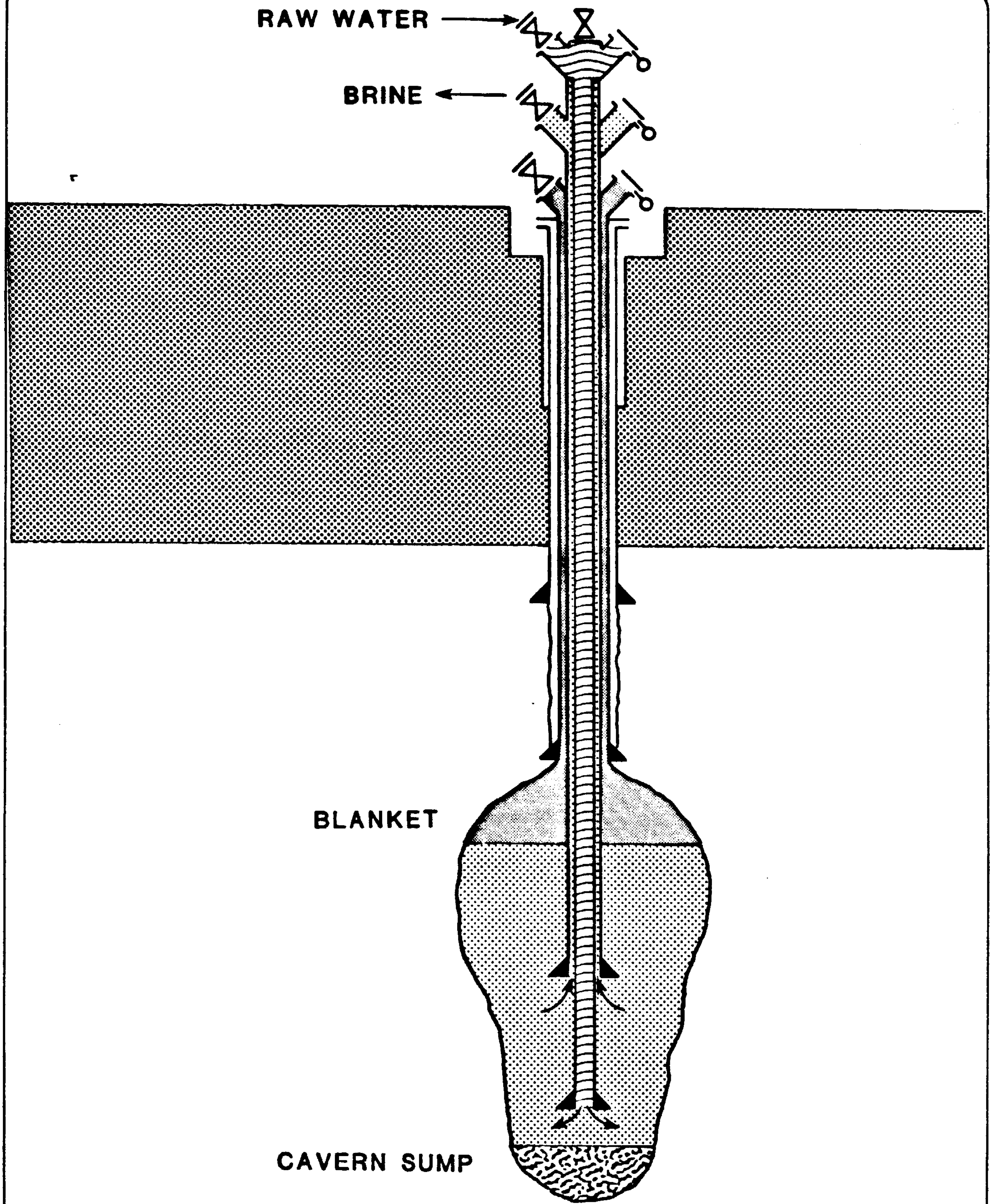

Fig. 7–Schematic for direct leaching.

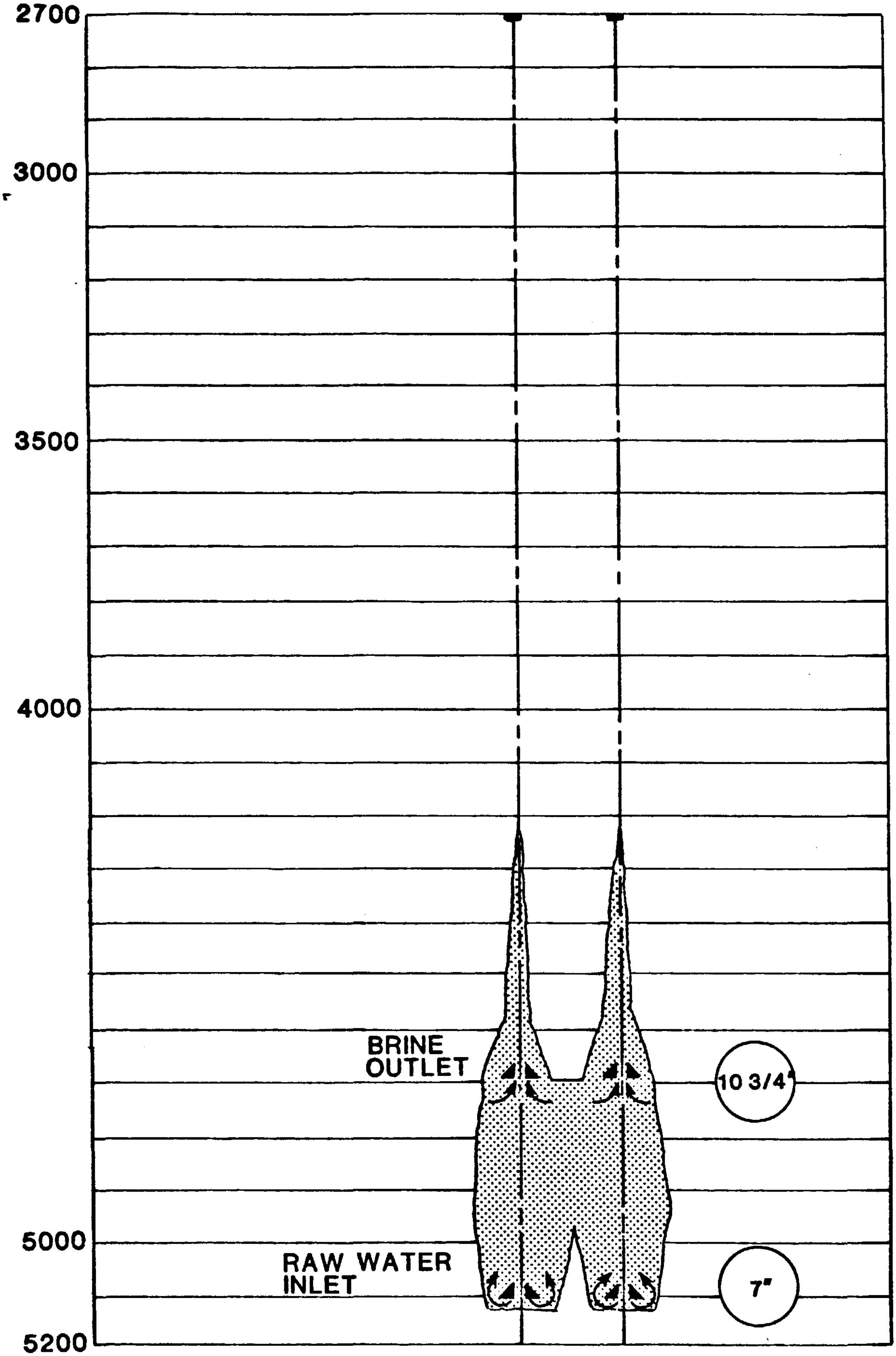

Fig. 8–Sump development in a cavern.

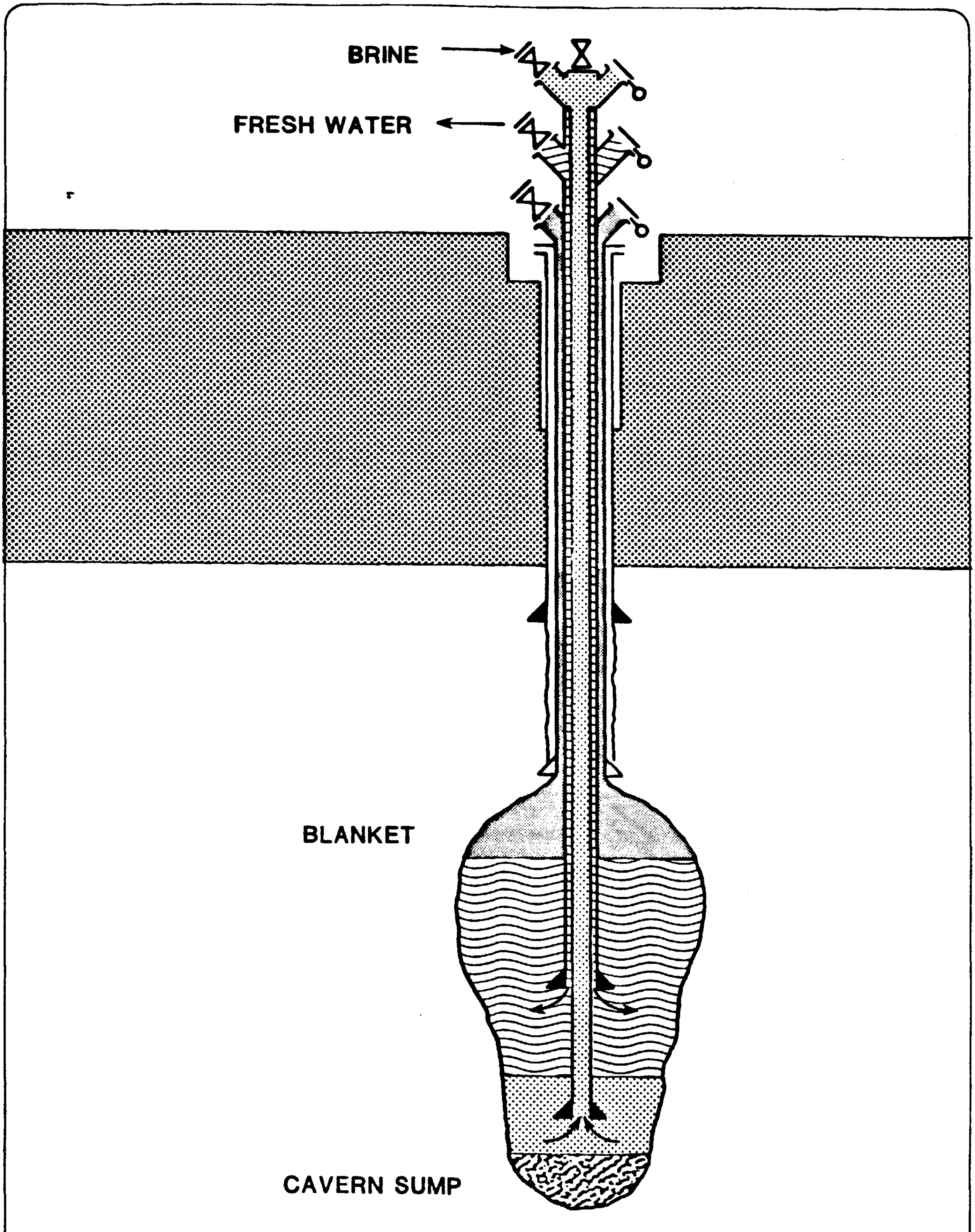

Fig. 9–Schematic for indirect leaching.

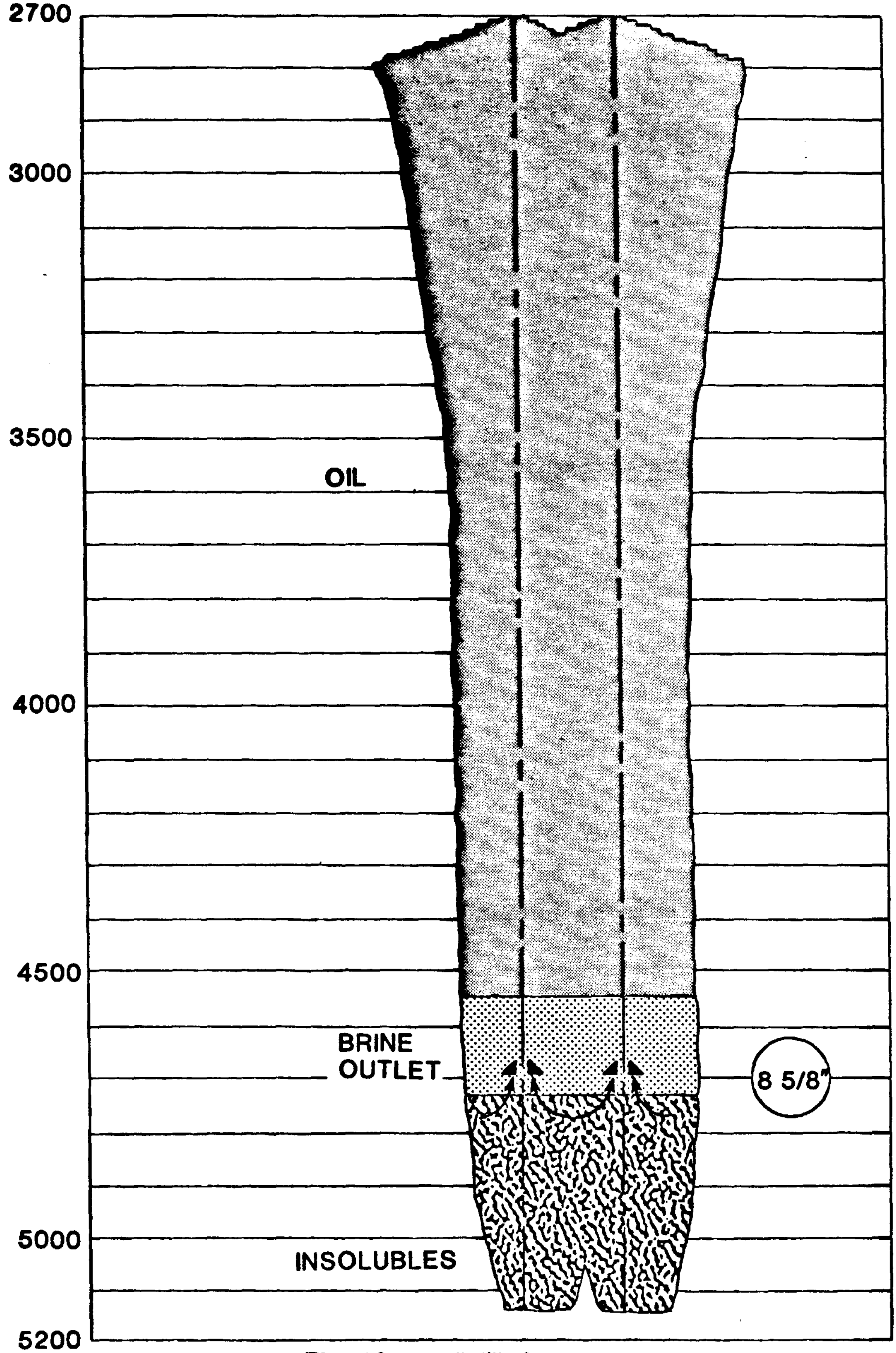

Fig. 10–An oil-filled cavern.

PB-KBB Inc.
Subsurface Systems & Technology
HOUSTON, TEXAS

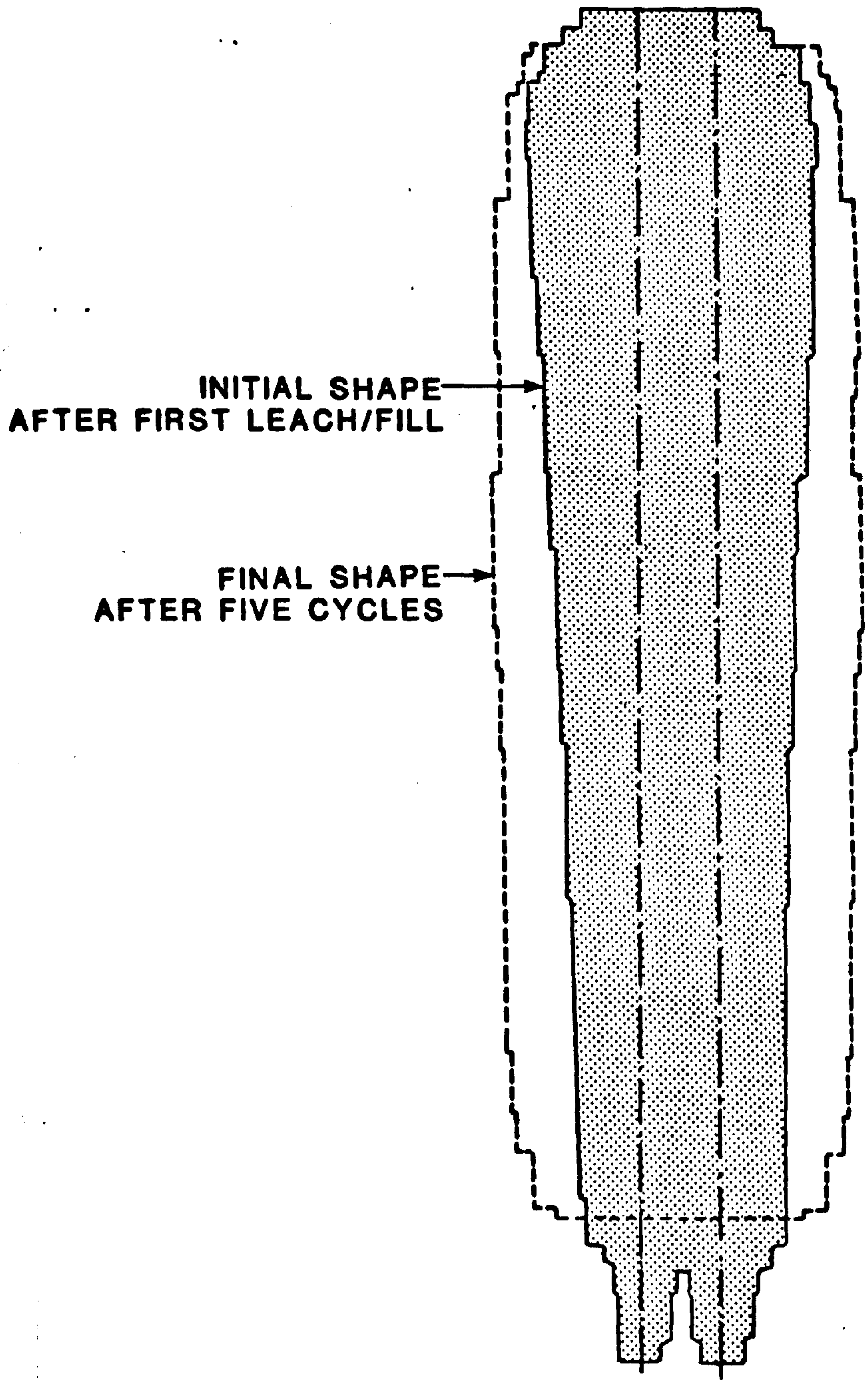

Fig. 11–Flower Pot Cavern–initial and final shape.