NATIONAL PETROLEUM COUNCIL

REPORT OF THE COMMITTEE ON UNDERGROUND STORAGE FOR PETROLEUM

APRIL 22, 1952

HEADQUARTER OFFICE

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1625 K Street, N.W.
Suite 601
Washington 6, D.C.

REPORT

of the

TECHNICAL SUBCOMMITTEE

of the

NATIONAL PETROLEUM COUNCIL'S
COMMITTEE ON UNDERGROUND STORAGE
FOR PETROLEUM

April 22, 1952

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NATIONAL PETROLEUM COUNCIL
REPORT OF THE COMMITTEE ON UNDERGROUND STORAGE
FOR PETROLEUM
APRIL 22, 1952

MEMBERS OF THE
NATIONAL PETROLEUM COUNCIL

Gentlemen:

Your Committee submits herewith report on the feasibility of underground storage for petroleum. The work on this study has been very ably carried out by a Technical Subcommittee under the chairmanship of Mr. B. F. Hake of Gulf Oil Corporation. Your Committee wishes to express its gratitude and appreciation of the excellent way in which these studies have been carried out.

It is the recommendation of your Committee that this report be given widespread distribution throughout the oil industry. Thereby, the normal operation of individual initiative in our system of free enterprise will undoubtedly result in so much development of the underground storage of petroleum that in a year or so a report on the subject will be essentially a record of achievement rather than a survey of possibilities and feasibility.

As an illustration of the already existing interest in underground storage we should mention that a quick survey indicates that there is already under way or in operation underground storage facilities, mainly for liquefied petroleum gases to the extent of about 7 million barrels.

H. S. M. Burns, Chairman
Committee on Underground
Storage for Petroleum

UNDERGROUND STORAGE FOR PETROLEUM

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UNDERGROUND STORAGE FOR PETROLEUM

A Report of the Technical Subcommittee
of the
Committee on Underground Storage for Petroleum
of the
National Petroleum Council

INTRODUCTION

The studies on which this report is based were made individually by the members of the subcommittee and by other interested individuals who were specially qualified to contribute valuable data and advice. These studies were coordinated primarily by collaboration in functional working groups and subsequently resolved, in general meetings, into this presentation, to which all members of the subcommittee subscribe.

The subcommittee's work could not have been accomplished without the generous support of the many individuals and corporations upon whose data and facilities the members of the subcommittee were privileged to draw.

Special acknowledgments are due to Mr. G. H. Billue of Hydrocarbon Storage Inc., who furnished the subcommittee with valuable advice and engineering estimates derived from his practical experience; Mr. R. L. Loofbourow of the B. J. Longyear Company, who furnished valuable information related to mining operations; Mr. Paul Weaver of Gulf Oil Corporation, who opened to the committee his rich store of precise data on the nature and occurrence of salt domes and salt deposits; and Messrs. R. H. Carr and L. L. McDonald, The Pure Oil Company, who inspected a salt mine and reported on it to the committee.

Three conclusions were reached by the subcommittee at an early stage of its work. <u>First</u>: The creation of underground cavities can, under a variety of conditions, provide storage for petroleum and petroleum products, with attendant economies of effort and steel and with a desirable factor of safety; Second: The determination of where and how and at what cost satisfactory underground storage may be provided, for specific substances, can now be indicated only in the broadest generalities; Third: Specific designs must be made in the light of detailed studies of specific locations and projects, and in the light of experience with a variety of methods, many of which are now virtually untested.

This report, therefore, is intended only to present attractive possibilities envisioned by the subcommittee; to warn of the hazards that the subcommittee has been able to recognize, and to indicate some of the means by which this useful device may be developed beneficially.

CONCLUSIONS

The subcommittee is unanimously of the opinion that underground storage of petroleum is feasible, offers important advantages and involves serious hazards, as indicated below.

Feasibility

1. Underground storage of petroleum and petroleum products is feasible and economic, under a considerable variety of conditions. A number of such projects are now either in process of construction or in actual operation in the United States and abroad; and some of the processes involved are covered by patents or patent applications.
2. In five areas of the United States (see Appendix I) it appears that creation of cavities in salt will be feasible. In five other extensive areas cavities mined from hard rocks such as granites, lavas, or metamorphics would be the only available means.
3. Extensive areas, totalling more than half of the United

States, are occupied by sedimentary rocks in which it will be practicable, in selected localities, to create underground reservoirs by mining in shale. Many natural underground reservoirs are also present in these areas.

4. Widespread in the United States are mines and natural caverns, some of which may be adaptable to storage of petroleum.

5. Properly constructed underground storage at suitable sites can, if necessary, meet any foreseeable need for stockpiling of crude oil or finished products, provided the possible effects of contamination, temperature, and time (see Appendix II) are recognized and compensated for.

6. Similarly, underground reservoirs could satisfy part of the industry's storage requirements occasioned by normal growth or need for replacement. In certain areas, for purposes of normal expansion of storage facilities, steel might be saved (see Appendix III) most expeditiously and effectively by constructing underground storage for crude oil and converting existing steel storage to use for products.

7. Purely economic considerations may, in many instances, dictate the substitution of underground for storage facilities (see Appendix III).

Apparent Order of Preference

Having regard to the factors of satisfactory operation and economies in steel, manpower, and dollars, it seems now that underground petroleum reservoirs might be preferred in the following order:

1. Cavities dissolved from salt deposits where they have adequate thickness and purity.
2. Existing mines where the problems of sealing are not too great and where there is proper expectation of long-term roof stability.
3. Cavities created by the mining of shale, where the shale deposits have the necessary strength and freedom from open fractures or contaminants.
4. Cavities created by mining hard rock, having due regard to the possibility that if open fractures exist it will be necessary to seal them from within; that the seals might not prove to be permanently effective; and that an underground reservoir, once occupied by petroleum, would, if damaged, be difficult or perhaps impractical to repair.
5. Traps in naturally permeable rocks such as structural domes, and sedimentary lenses. These have the disadvantages of resistance to injection and withdrawal, and the possibility of high initial losses when the fluid to be stored is first introduced into the permeable medium.
6. Natural caverns, which may prove, in some instances, to be readily adaptable to the storage of crude oils and petroleum products of low vapor pressure, but which may present very serious problems of sealing, since the presence of a natural cavern indicates permeability of the stratum in which it occurs. This problem is especially serious in projects involving storage of high vapor pressure products.
7. Abandoned coal mines, which are believed to offer relatively little promise because coal normally contains substances that

would contaminate finished products to an unacceptable degree, and also because coal is a relatively weak structural material and is often closely associated with permeable rocks.

Factors Affecting the Feasibility

1. One of the factors important in the economic success of underground storage in salt formation will be relationship between the cost of drilling to the necessary depth and the size of the cavity that it is practical to create at that depth.
2. A factor essential to the success of any underground storage venture is the careful exploration of the site by means of core drilling and intensive study of the recovered cores for the determination of their physical and chemical characteristics and the presence or absence of objectionable contaminants, which operations should be conducted thoroughly in advance of any actual construction.
3. Contaminants likely to be encountered are, among others, sulfur, hydrogen sulfide, hydrocarbon gases, and hydrocarbon residues. While some of them may not harm crude petroleum, if such is to be stored, they will in one way or another seriously affect the quality of stored refined products. It is, therefore, all-important that any exploration undertaken to establish the geology of a particular deposit include a careful analysis of core samples in order to establish quantitatively the presence of harmful contaminants.
4. Other factors that must be taken into consideration, in order to guard against deterioration of certain products in storage, are the effects of time and temperature, which, even in the

absence of oxygen, can cause certain components to polymerize and degrade the performance quality of refined products.

5. Another factor that has profound bearing on the value of the underground storage for petroleum is the location of the reservoirs so that they will not create transportation problems outweighing their own natural advantage.

6. Since it appears desirable that every underground reservoir shall have a domed or vaulted roof with relative steep inclination, it may prove unsafe to allow the horizontal dimensions of such reservoirs greatly to exceed their height. Therefore, in the construction of underground reservoirs in bedded salt deposits of limited thickness - relatively small individual reservoirs only will be practical. The economic advantage of such construction will finally disappear with depth of overburden, making such attempts inadvisable unless economy of steel or manpower, as such, should dictate the attempt.

Considerations Related to Public Safety

1. Reservoirs should be entirely enclosed in rocks that are effectively and permanently impervious by nature or made so by artificial means, except where the contents will be positively confined by ground water. Prominent among the impermeable rocks are salt, gypsum, igneous rock, dense limestone and shale, providing in all cases that these rocks are not cut by fractures along which fluids might migrate.

2. In order to guard against possible fracture of the reservoir by internal pressures, each reservoir should be under cover of more than one foot of depth for each pound of total maximum pressure

(hydrostatic plus vapor plus pump) that may at any time exist within it, having due regard to the underground temperature in the locality and the depth considered. The additional thickness of cover that should be provided as a factor of safety must be determined for each individual case.

3. Competent engineering supervision should make certain that the roof of each reservoir is in rocks of sufficient strength and is designed in such manner as to preclude dangerous caving or upward fissuring.
4. All connections between the reservoir and the surface should be so sealed as to preclude possibility of any fluid leakage, either upward or downward at any level and this condition should be demonstrated by adequate pressure tests before any petroleum is introduced into the reservoir.
5. Reservoirs should preferably be located outside the limits of municipalities.
6. Each reservoir should be separated from any other reservoir or underground excavation (actual or potential) by sufficient distance to preclude possible intercommunication.
7. Extreme care should be exercised in the construction of rese-voirs to avoid rocks that could provide avenues of escape for the contained petroleum from the reservoirs.

Continuation of Work Started by This Subcommittee

This Committee recognizes the desirability of continued study of possibilities of underground storage of petroleum and refined products, in various parts of the United States, and the dissemination of information concerning such.

It is recommended that the National Petroleum Council should suggest to the Secretary of the Interior that, through appropriate channels, he invite each State Geologist to serve as chairman of a permanent State committee, the membership of which should include geologists and engineers drawn from the petroleum and mining industries, and that such committee in each instance should study and issue occasional reports upon the possibilities, initiation, and progress of the establishment and maintenance of underground storage of crude petroleum and refined products, and that further, the Department of the Interior should announce that it is prepared to promote this effort by consultations with the State Geologists and by serving as a clearing house for such information as their committees may collect and release.

Appendix I

SOME GEOLOGIC ASPECTS OF SUBSURFACE STORAGE

General Geologic Situation

Possibilities for subsurface storage of the different types that have been discussed could probably be best described for the United States by regions or districts, starting in with the Atlantic Seaboard. See Plate I. On Plate II there is presented also a generalized rating of the different types of reservoirs.

The northern portion of the Atlantic Seaboard, from New Jersey to the Carolinas, consists mostly of a coastal plain, in which area the only possibilities would appear to be the mining of shale cavities and the possibility of injection storage into lenticular wedges of sand.

The southern portion of the Atlantic Seaboard, in Georgia and Florida, does not appear to have favorable possibilities for subsurface storage due to the character of the sediments; sands and limestones from shallow depths, being considered too porous to be favorable for developing storage.

The Appalachian core, consisting mostly of granitic rocks, extends from Maine southwestward into Georgia and eastern Alabama. In this long, narrow strip the only possibility of storage would be confined to mining of cavities in hard rock.

• Westward of the Appalachian core is a folded belt of sedimentary rocks where complicated structural features could possibly include natural rese-voirs in porous rocks for storage by injection methods. This area could also be considered as possible for mining reservoirs in shale or limestone.

The Appalachian Basin, which includes the salt bed series of western New York, Pennsylvania and eastern Ohio, and the Michigan Basin, are described and discussed in the following section on possible salt reservoirs.

In the central states a favorable type of storage would be practically confined to the mining of sedimentary beds with some slight possibility of structural deposits that might be susceptible to injection for storage.

A portion of the central states, known geographically and geologically as the Ozark Uplift, would not appear to be favorable for construction of subsurface storage of petroleum products due to the mineral content of the rocks. This is a lead and zinc mining district.

The Ozark Basin, south of the Ozark Uplift, is an area of thick sedimentary formations that could be considered possible for mined cavity storage.

South of the Ozark Basin is the salt dome area of the Gulf Coast, where development of storage in salt domes is recognized as favorable and discussed on following pages.

Westward from the Gulf Coast is the central Texas Sabine Arch, which includes a large area of sediments and some hard rocks that might be possible for mining cavities for storage.

Westward from the central Texas area is the Permian Basin which has been given a priority in storage possibilities due to the presence of rather wide-spread salt deposits extending from southwest Texas into north central Kansas. This area also provides opportunities for construction of cavities by mining of shales.

North of the Permian Basin, between the Mississippi River and the front range of the Rocky Mountains, there exists a large area of sediments in which shale bodies may be considered favorable for mined storage cavities, and in which there are many natural reservoirs in permeable strata, some of which might prove to be of practical utility.

The backbone of the Rocky Mountains, extending from Montana southward into southern New Mexico, would have only the possibility of hard rock mining for storage purposes.

Within the general area of the Rocky Mountains there are several separate sedimentary basins where favorable reservoir site are possible, either in porous rocks of favorable structures or by the mining of shale beds. This area also includes one not large area of salt in the Paradox Valley of southeastern Utah and southwestern Colorado, where salt cavity reservoirs could be favorably considered.

In the Great Basin Area of Utah, Arizona and Nevada, which is a highly folded and metamorphosed district, storage possibilities are probably confined to the mining of cavities.

Southwest and north of the Great Basin District is a large volcanic area extending from southwestern Texas across southern Arizona through Nevada, eastern California, eastern Oregon, Idaho and Washington to the Canadian border, where it is doubtful if any favorable consideration can be given for construction of subsurface storage.

In the Pacific Coast area west of the Sierra Nevada and the Cascade ranges are several sedimentary basins where sufficient folding is present and structural conditions favorable for sand reservoir injection, and where shale could be mined for storage of petroleum products.

Salt Deposits for Underground Storage

General

The term "Salt" or "rock salt" as used in this report means any massive body of water-soluble rock consisting principally of sodium chloride though often containing traces or small amounts of gypsum, anhydrite, potash, etc. While any readily water soluble rocks of sufficient purity, thickness, and extent might be suitable for the solution of storage cavities, no appreciable quantities of such rocks, other than rock salt are known in the United States. Veins, stringers or thin beds of salt a few inches to a few feet thick between beds of other rocks, and clastic rocks such as sandstone containing interstitial salt are not included in the present descriptions of salt deposits.

Two chief types of rock salt deposits are known in the United States: bedded or sedimentary rock salt and intrusive rock salt, the latter commonly found as salt domes.

Bedded rock salt occurs in the Great Lakes district in the northern Appalachian geosyncline, and in the Michigan Basin, underlying parts of the States of New York, Pennsylvania, West Virginia, Ohio, and Michigan, and in a large area of the south-central states known as the Permian Basin, where it underlies parts of Kansas, Oklahoma, Texas, and New Mexico. Salt domes are known on the Gulf Coast from the Mexican border to and possibly including parts of western Alabama, in a broad band reaching inland from the coast approximately 80 miles at Corpus Christi to 225 miles north of Port Arthur, Texas. An intrusive flow of rock salt is found in a comparatively small region of southeastern Utah and southwestern Colorado.

Within each of the foregoing areas there are sufficient quantities of salt of adequate thickness so that almost unlimited storage could be developed. Therefore, the storage requirements as given to us by the Transportation Group, where they can be met at all, with rock salt cavity storage, can be met in full.

There are within the salt dome areas a sufficiently large number of shallow domes so that no consideration is given in this report to domes which may be found below depths of several thousand feet.

P.A.W. District I

P.A.W. District I, as shown on the accompanying map, comprises West Virginia, Pennsylvania, Vermont, and the East Coast states bordering on the Atlantic Ocean.

The Syracuse rock salt beds of the Upper Silurian (Salina) formation on the west flank of the Appalachian geosyncline, underlie parts of southwestern New York, western Pennsylvania, and northwestern West Virginia. The nearest Syracuse rock salt to a large refining center is in the Ithaca area of New York State, where it lies approximately 190 miles from New York City and the refineries of the New York City area, as shown on Plate II.

Rock salt of the Syracuse formation occurs in beds of variable thickness and overlapping lenses with intervening layers of anhydrite, dolomite, and clayey salt. The lenses are sometimes 30 feet thick over an area of several thousand acres.

A known stratigraphic succession of the layers of these materials in the rock salt beds cannot be predicted to extend for more than a few hundred feet distance. Well logs and mining records show that the maximum thickness of a single layer of Syracuse rock salt may be 40 to 70 feet.

The Syracuse rock salt beds outcrop in a westerly direction from Syracuse, New York, and dip southeasterly at around 45 feet to the mile so that at Elmira near the Pennsylvanian border their top is approximately 2500 feet below sea level or at a depth of 3500 feet below the surface. Westward from Ithaca the salt beds obtain a thickness of some 150 feet but gradually pinch out and are not present in the vicinity of Buffalo and the New York shoreline of Lake Erie. At Franklin and Oil City, Pennsylvania, the Syracuse rock salt is perhaps 130 feet thick and about 4000 feet below sea level, or at a depth of 5000 feet below the surface. At Pittsburgh, Pennsylvania the top of the salt beds are mapped at a depth of 7300 feet below sea level or at a depth of approximately 8200 feet below the surface. Continuing southwestward into West Virginia the Syracuse salt formation terminates some sixty miles northeast of the city of Charleston, West Virginia.

The same Syracuse salt may underlie eastern West Virginia and parts of western Maryland but farther west it grades into sandstones or shales. There are insufficient data available at this time to enable us to be certain of the presence of salt in this area.

P.A.W. District II

This district is made up of fifteen Mid-continent states between Pennsylvania on the east, Colorado on the west, Texas and Arkansas on the south, and the Canadian border on the north.

Within District II, as shown on the accompanying Plate II, rock salt formations are confined to Michigan and eastern Ohio. In eastern Ohio the salt is a westward continuation of the rock salt underlying western Pennsylvania in Area I. West of a line running through Mansfield, Zanesville, and Marietta, Ohio, the Syracuse salt pinches out. East of Marietta the salt is found at a depth of about 5500 feet. This is the maximum depth of its occurrence in Ohio. At Cleveland, Ohio the top of the rock salt lies approximately 1200 feet below sea level (2000 feet below the surface) and totals approximately 70 feet in thickness.

The salt beds of Michigan lie within a basin which includes most of the state. They are recognized geologically as belonging to the Saline formation of Upper Silurian age similar to the deposits on the west flank of the Appalachian geosyncline in western New York and Pennsylvania.

Near the center of Michigan's lower peninsula the Salina rock salt, found at approximately 5000 feet below sea level, has an aggregate thickness of some 1800 feet. Outward from this point the salt thins and becomes shallow so that in the vicinity of Detroit its topmost members are approximately at sea level, i.e., 300 to 400 feet below the surface. The salt in this locality totals approximately 400 feet in thickness.

In the southwestern portion of District II the rock salt of the Permian Basin occurs stratigraphically in Upper Permian formations and is geologically known as the Permian Salt. It underlies much of central and western Kansas and the Panhandle of Oklahoma. Throughout most of south-central Kansas and eastern Oklahoma Panhandle it lies about 600 feet below the surface and has an average thickness of 100 to 200 feet. It attains a maximum thickness in Hutchinson County, Kansas, about 40 miles west of Wichita, and in an area surrounding and including Clark and Comanche Counties, Kansas, where a second salt zone occurs higher in the section and locally increases the total rock salt thickness to over 300 feet.

The Permian rock salt appears to be a series of lenses of rock salt, anhydrite clays, and sandstones, interfingered with one another. The total thickness of rock salt and the thickness of any one salt bed may vary considerably within short distances. However, in western Oklahoma and Kansas well log data show a fairly continuous thickness of 50 to 70 feet for the rock salt beds. Impurities in the Permian rock salt consist mainly of the same materials that interfinger with it - anhydrite, sands, clays, and small percentages of polyhalite.

P.A.W. District III

As shown on Plate II, this district includes New Mexico, Oklahoma, Arkansas, and the remaining Gulf Coast states except Florida. The Permian salt extends throughout the geological province known as the Permian Basin in eastern New Mexico, west-central Texas, and the Panhandle of Texas. It varies in thickness from a few feet at its edges to 1400 feet in several counties near the southeast corner of New Mexico. It appears to be lenticular and interbedded with streaks of anhydrite, sandstones, and clays which are hundreds of feet thick in places. Individual salt beds 100 feet and more in thickness have been logged in most of the area. Its impurities are the same clays, sandstones, anhydrites, dolomites, and polyhalites as in the District II portion of the Basin.

At Amarillo, Texas, the rock salt is about 650 feet thick and its top is about 450 feet below the surface. At Wheeler the top of the salt is around 900 feet deep and has a thickness of 150 feet, while in Scurry, Mitchell, and Sterling Counties, Texas, the salt is less than 100 feet thick.

In the coastal area of District III more than 200 salt domes which lie at or near the surface are known to be present. Some of these domes are only a few thousand feet in diameter, but the average width is probably between one and two miles. An average depth of the top of the salt is probably between 500 and 1000 feet. The thickness of the salt itself in the domes is not known but may be 10,000 feet or more. The salt comprising the domes is very massive and almost pure sodium chloride. Most of the salt domes are overlain by cap rock of anhydrite, gypsum, and dolomite. Sulphur is a commonly occurring mineral on the flanks and on the cap rocks of the salt domes, but the salt itself seems to contain very little sulphur or sulphur compounds. Such impurities as do exist in the salt are mostly very small quantities of anhydrite, gypsum, and dolomite. The salt is almost completely free of clay minerals. Within a few miles of any Gulf Coast refinery, shallow salt domes are available to provide any conceivable amount of required storage.

P.A.W. District IV

This district includes the Rocky Mountain states of Montana, Idaho, Wyoming, Utah, and Colorado, within which there is one area of rock salt, which includes a small portion of southeastern Utah and southwestern Colorado. A distance of one hundred and fifty miles and the elevated area of the Wasatch Mountains separates this salt area from the nearest refinery which is at Salt Lake City, Utah.

P.A.W. District V

This district consists of Arizona, Nevada, and the West Coast states. A rock salt deposit of small areal extent is found in the southeastern corner of Nevada along the Virgin River about 40 miles east of Las Vegas. While the rock salt here attains a thickness of 100 feet or more, the area is severely folded and faulted and is not believed to be of importance for storage. This locality is also far from refining and population centers and at present largely inundated by the waters of Lake Meade.

We wish to acknowledge use of maps and data furnish by Messrs. G. H. Billue of Hydrocarbon Storage, Inc. and Paul Weaver of Gulf Oil Corporation.

Further selected bibliography:

Landes, Kenneth K. - U.S.G.S. Oil & Gas Investigations Preliminary Map 40-1945
Hoots, H. W. - U.S.G.S. Bull. 780
Bass, N. W. - Kansas Geol. Survey Bull. No. 11, 1926
Kindle, E. M. - U.S.G.S. Bull. 260
Phalen, W. C. - U.S.G.S. Bull. 669
Kroenbeim, George A. - A.A.P.G. Bull. 23 - 1939
Various authors in A.A.P.G. Volume on Salt Domes - 1926
Baltimore and Ohio Railroad Salt Report

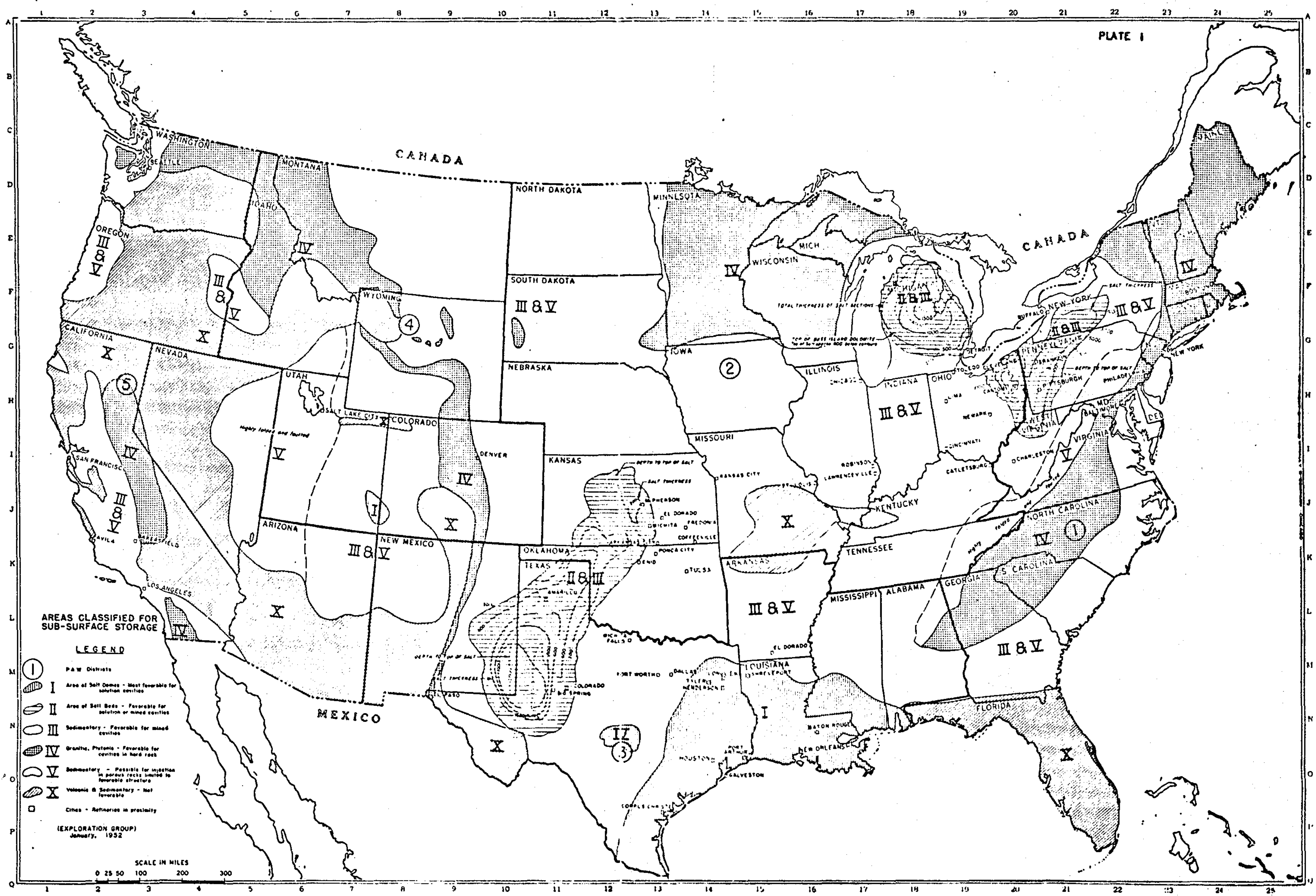
PLATE I
CANADA
MEXICO
AREAS CLASSIFIED FOR SUB-SURFACE STORAGE
LEGEND
P A W Districts
I Area of Salt Domes - Most favorable for solution cavities
II Area of Salt Beds - Favorable for solution or mined cavities
III Sedimentary - Favorable for mined cavities
IV Granite, Plutonic - Favorable for cavities in hard rock
V Sedimentary - Possible for injection in porous rocks limited to favorable structure
X Volcanic & Sedimentary - Not favorable
Cities - Refineries in proximity
(EXPLORATION GROUP)
January, 1952
SCALE IN MILES
0 25 50 100 200 300
WASHINGTON
SEATTLE
OREGON
IDAHO
MONTANA
WYOMING
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
CALIFORNIA
NEVADA
UTAH
SALT LAKE CITY
COLORADO
DENVER
KANSAS
ARIZONA
NEW MEXICO
OKLAHOMA
TEXAS
SAN FRANCISCO
LOS ANGELES
MINNESOTA
WISCONSIN
MICH
IOWA
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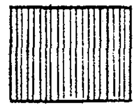
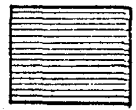
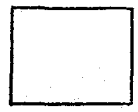
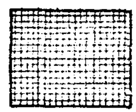
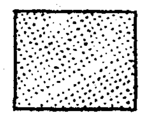
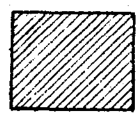
TENNESSEE
ARKANSAS
MISSISSIPPI
ALABAMA
GEORGIA
LOUISIANA
FLORIDA
NORTH CAROLINA
S. CAROLINA
VIRGINIA
WEST VIRGINIA
PENNSYLVANIA
NEW YORK
MAINE
AMARILLO
FORT WORTH
DALLAS
HOUSTON
GALVESTON
BATON ROUGE
NEW ORLEANS
EL DORADO
TULSA
PONCA CITY
COFFEYVILLE
CINCINNATI
CHARLESTON
PITTSBURGH
PHILADELPHIA
BUFFALO
DETROIT
TOLEDO
BIG SPRING
PORT ARTHUR
III & V
IV
X
I
II & III

GENERALIZED CLASSIFICATION, UNDERGROUND RESERVOIRS

Type of Reservoir	RATING BY FACTORS				Economic Preference Rating	Map Symbol (Plate I)
	Cost of Construction	Lack of Contaminants	Cost of injection & recovery	Total of factor ratings		
Solution Cavity in Salt-dome	1	1	2	4	I	
Solution Cavity in bedded salt	1	2	2	5	II	
Mined Cavity in shale or salt	3	2	1	6	III	
Mined Cavity in hard rock	5	1	1	7	IV	
Natural Trap resevoir in porous rocks	1	3	4	8	V	
Abandoned mine or natural cavern	3	5	1	9	VI	No Map Symbol. Would be rated high if easy to seal.
Underground storage considered impractical in areas of volcanic rocks, mineralization, extremely complex structure, or excessive general permeability.						

Appendix II

SOME CHEMICAL ASPECTS OF UNDERGROUND STORAGE

Within the scope of activities outlined for the Technical Subcommittee in letter of September 4, 1951, H. A. Stewart to James V. Brown, the following items have a direct bearing on the objective of the Refining Group of this subcommittee.

1. Products stored should be ready for use.
2. Stored products should meet qualified standards for civilian usage.
3. Storage should be considered substantially dormant, but if and where practical it might be made subject to periodical turnover to reduce deterioration.

In addition, it was stated that "The petroleum products to be considered should be gasoline, kerosene, distillate, residual fuel oil, and should include liquefied petroleum gases."

In order to fulfill this assignment, Group III outlined the following objectives:

1. Set forth product specifications and respective limits considered necessary for assuring performance quality;

2. Determine effect of storage conditions (time, temperature, pressure, contact agents, contaminants) on quality criteria and performance of products;

3. Determine means for preventing deterioration or correcting deterioration should it occur.

Objective I

It was brought out in the discussions of the Subcommittee that whereas the directive from the U.S. Department of the Interior, Oil and Gas Division, stated that "stored products should meet qualified standards for civilian usage", it would be more expedient and realistic to adopt Military and/or Federal specifications, for the reason that -

1. Such specifications are generally recognized by the industry, and with few exceptions specify product quality suitable for civilian usage.

2. In the event of a national emergency some or all of the stored products could be diverted for military use, if required.

The Refining Group has not attempted to appraise the listed specifications for their quantitative value for gauging performance quality, but has accepted them as qualified standards for civilian and military usage. This position seems justified in view of the fact that many years of background and experience have preceded their formulation. It should be understood, however, that efforts toward improving performance criteria are continuing. These can be expected to produce specification changes.

Objective 2

Since it is desired to draw the products from underground storage ready for use, it must be presumed that the listed specifications will be met <u>after</u> an undefined period of storage. This requirement necessitated an understanding of the effect of various factors that will, and others that may, be encountered.

The known factors are temperature, pressure, and contact with brine and/or salt, if salt domes or salt mines are chosen for the storage of products.

The unknown factors are composition of products, time, contaminating agents, and the compatibility of products.

The latter is important if the products are drawn from more than one source of dissimilar composition.

Before an opinion could be rendered on the probable effect that the unknown factors may have on the stored products, it will be necessary to define them and to establish their magnitude; in other words, specific information will be required on location, type and volume of products to be stored, time of storage, and the various factors that may cause the degradation of the stored products.

The latter can be divided into three major categories:

1. <u>Instability</u>

This can be defined as susceptibility to oxidation and/or polymerization. Both types of reaction occur predominantly with unsaturated hydrocarbons (olefin and diolefin), such as are found in many gasolines, heating oils, bunker fuels, and even some diesels. Oxidation need not be troublesome if air can be excluded from contact with the stored product and if the dissolved oxygen content of the product has been adequately neutralized by the addition of accepted oxidation inhibitors.

In the well type of storage, contact with air can be prevented by maintaining the differential pressure of a column of brine against the product up to the well head. In other types of storage, such as salt mines accessible through a shaft, other means for excluding contact with air will have to be devised.

Polymerization may result from subjecting the product containing unsaturated hydrocarbons to heat and pressure for prolonged periods of time. It is known that concentration has a marked effect on the rate of polymerization. Certain agents will promote this reaction. Among these, ferric oxide and ferric chloride are given as examples. In their presence the rate of polymerization will be accelerated. At a depth of 2,000 ft., a column of brine will exert a pressure of approximately 1,000 lbs. per sq. in. If the geothermal gradient is 72 ft. per degree, the temperature at 2,000 ft. depth would be approximately 30° higher than at the surface. Reaction rates have been established for many pure hydrocarbons at temperature levels much higher than will be encountered in underground storage. Reaction rates at lower temperature levels can be calculated. Data, however, are not available for complex hydrocarbon mixtures such as constitute most of the petroleum products. Experimental work remains to be done for determining reaction rates on these complex mixtures under conditions likely to be found (say 150°F., 2,000 lbs. pressure). Choice of location and definition of product to be stored should logically precede the initiation of such a program.

2. Incompatibility

As explained previously, this term defines a reaction among components of products of the same general type but of different composition. Although each such product by itself may be quite stable, interaction when they are mixed may produce unfavorable results.

This problem has for many years been recognized by the Navy in connection with the Special Fuel Oil. Satisfactory control has been achieved by the requirement that each supplier submit a sample of the fuel oil that he proposes to manufacture for the Navy under contract to the Naval Boiler Laboratory, where it is blended with a group of selected oils (specified by the Navy) and subjected to a special test which it must pass in order to meet the compatibility specification.

Many units within the industry are becoming concerned about the incompatibility and lack of stability disclosed by certain diesel fuels; for example, General Motors has found that samples of a virgin and a cracked diesel fuel component each by itself showed no sediment formation after one day's exposure to light. However, a 50/50 blend of the two, under the same conditions, developed a heavy sediment.

It is also reported that the Bureau of Mines (Mr. H. Smith) is currently engaged on a distillate fuel laboratory storage program in cooperation with the Western Petroleum Refiners Association. The work will include an investigation of the effect of crude source, cracking process, concentration of cracked material, and storage conditions. Another program is being conducted by the Navy, Bureau of Ships, involving the study of the behavior of Diesel fuels in ships' tank storage. In view of this general interest and the trend in the field toward subjecting Diesel fuels to longer and longer storage periods, particularly by the railroads, the Panel on Jet and Diesel Fuels of the CFR Storage Stability Group agreed that there was a problem on Diesel fuel stability and compatibility that required investigation. A sub-group has been appointed to draw up a program covering laboratory storage, field storage, and engine tests. It will be pertinent to keep in close touch with the findings of this group and in due course of time adopt specification restrictions that will control the above-mentioned product deficiencies.

It is not possible at the present time for Group III to make a specific recommendation as to how this problem could be controlled, except in the case of Special Navy Fuel Oil for which a suitable test procedure has been established, but it may be expected that the activities outlined above will provide bases for definite recommendations under appropriate circumstances.

3. Contamination

As brought out in the discussion by Mr. Paul Weaver, and as has been indicated by others, contaminants of various types can be encountered in salt domes. The most important appear to be sulfur, hydrogen sulfide, hydrocarbon gases, and hydrocarbon residues. Carbon dioxide also must be considered. A comprehensive discussion of the effect of each of these on the specification limits of the various products is considered beyond the scope of this progress report. It can, however, be stated that each of the contaminants can degrade the various products to an extent dependent upon the degree of contamination. For example, hydrocarbon gases will increase the vapor pressure of L.P.G. and gasoline and will lower the flash point of the remaining products. The explosivity of fuel oil can be raised beyond the limit specified by the Navy.

Sulfur and hydrogen sulfide will mainly affect the corrosion specification of the various products with the exception of fuel oil, which has no such restriction. On kerosene, free sulfur can increase the tendency to char wicks and on gasolines the lead susceptibility can be affected. Sulfur may well be found to be the most serious of the contaminants, in that extremely low concentrations in the order of parts per million are known to render certain products corrosive. For example, one part per million amounts to only one-quarter pound per 1,000 bbls.; therefore, contact with only 250 lbs. of sulfur can render corrosive 100,000 bbls. If free sulfur exists in strata interposed between layers of sodium chloride it would seem pertinent to establish by taking a core sample the number of such strata and their thickness before a dome is chosen for the storage of sulfur-sensitive products.

Hydrocarbon residues of the asphaltic type will degrade all products with perhaps the exception of residual fuels. They will affect color, Conradson carbon, "gum content", and, in the case of kerosene, will cause a deposition of char on the wick in lamps or range burners.

It is recognized that other contaminants may be encountered. It is believed, however, that those listed must be primarily searched for when choosing the location for an underground storage project.

Objective 2 is incomplete, mainly because specific information is lacking on the various items whose effect, singly or combined, will exert their influence on the quality of the products to be stored. Work is under way to establish "tolerances" for some of the contaminants in some of the products. How soon an answer can be given is not known at the present time.

No problem is foreseen in connection with the above for the storage of crude oils, because refining techniques have been established to cope with such contaminants.

Objective 3 - corrective measures. No comments on this phase of the problem can be given until type and degree of contamination have been established.

Appendix III

SOME ENGINEERING ASPECTS OF UNDERGROUND STORAGE

The matter of using underground formations for the storage of petroleum products (other than natural gas or crude oil) is a recent innovation.

The first project of this type that demonstrated a storage efficiency equivalent to steel tankage was a 7,000-barrel reservoir washed out of the Western Saline Section at Kermit, Texas, (Winkler County), in 1950. Since that time several million barrels of such storage have been created or are under construction, a majority of which are in New Mexico, Texas, Oklahoma, Louisiana, Mississippi, Kansas and Michigan.

In some areas, where water soluble rocks are at great depths or are not present, underground storage has been constructed or is under construction by mining operations.

The motivating force behind the petroleum industry's effort to develop underground storage stems primarily from the extremely high cost of steel tankage required to store the high vapor pressure products such as propane and butane. The storage of these products has become a critical problem for the industry because of the high seasonal fluctuations in demand, increased production, and governmental regulations on conservation.

In the subsequent discussion, estimates, and comparisons with surface storage, only those methods considered at present to be the more economically feasible have been set out; namely, cavities dissolved from salt deposits and cavities created by mining. The other possible methods considered in this review; namely, existing or abandoned mines, natural caverns and traps in naturally permeable rocks such as structural domes and sedimentary traps, have been purposely omitted from any economic review in that it is felt that variations in costs between specific projects of the same nature will vary so widely that no general approximation can be made or, initial recoveries are not comparable to a storage efficiency of surface storage; therefore, each particular project should be considered on its own merits.

The attached Plates I, II, and III set out the general comparison of cavities created by dissolving salt, cavities created by mining, atmospheric surface storage and pressure surface storage with respect to cost per barrel of storage, pounds of steel per barrel of storage, and man hours required per barrel storage. In general, for 100,000 barrels of storage, the following table reflects these comparisons:

Type of Storage	Cost per Barrel	Steel Requirement per Barrel	Labor Requirement per Barrel
Pressure Surface Storage	$ 20.00	98 lbs.	1.26 Man Hours
Atmospheric Surface Storage	1.09	7.5 lbs.	0.07 " "
Cavities by Dissolving Salt	0.75	1.5 lbs.	0.11 " "
Cavities by Mining	4.50	2.2 lbs.	0.37 " "

In arriving at the estimates reflected in the above tabulations, it was necessary to reduce all types of storage considered to a common denominator as well as to make certain assumptions in each instance to arrive at an appropriate comparative estimate. The following sets out, in general, the assumptions made in each instance in arriving at such common denominator.

1. Pressure Surface Storage

It was presumed in arriving at an estimated cost that such storage would be located at or near an already constructed storage; in such event, it would not be necessary to acquire a site nor construct railroad sidings and loading racks; however, appropriate piping, manifolds, loading and unloading pumps, etc., would be required. In consideration of steel requirements, minimum requirements to conform to current regulations and insurance requirements were used. Only that labor required for actual shop fabrication and field erection, including loading and unloading facilities, was considered.

2. Atmospheric Surface Storage

To reflect near comparable efficiency to pressure surface storage and underground storage, floating roof tanks were used for estimating purposes. Had cone roof tanks been used in estimating, estimated cost would have been around sixteen cents per barrel less. As with pressure storage, the location was assumed most convenient so as to effect minimum related requirements such as land acquisition, loading racks, etc.

3. Cavities by Dissolving Salt

In view of little, if any, necessity for geological exploration required to effect the efficient location of pressure surface storage and/or atmospheric surface storage as well as considerable geological information already being known relative to the location and depths of salt formations so as to effect minimum exploration requirements for this type storage, cost of exploration is not included in the estimates. It is presumed that the location of the storage can be picked so that fresh water is readily available at minimum cost, and loading rack facilities as well as a site is already available. A number of highly variable factors which effect cost are evident in making any estimates of this nature, a number of which are: well depth, formation thickness, casing pattern, salt water disposal facilities, cementing costs, drilling costs, etc. In arriving at the estimates reflected on Plates I, II, and III, two practical depths were chosen and reasonable casing patterns were assumed.

To date, there has been no firm figure established as to the maximum diameter to which a cavity can be washed out in a salt formation of a given thickness and consistency; therefore, in estimating costs beyond the cost of drilling and equipping the storage well for the various size storage, it is presumed that sufficient thickness of salt formation is available in the particular well to effect the maximum storage quantity reflected. With such an assumption, cost for increased storage becomes a function of the operating cost to dissolve out additional salt plus an additional expenditure to effect an appropriate size surface pit for storage of saturated salt water equivalent to the quantity of storage. Although deep well pumps can be used for removing stored products from such a storage well, installations to date have used saturated salt water as a displacement medium to remove the stored material. The estimates, therefore, included the construction of a surface pit equivalent to the capacity of the storage for use in storing the required salt water, with such construction so as to preclude the use of steel, as well as necessary pumping equipment, and related facilities. No surface storage, however, for the stored material is included.

Storage installed in this manner to date for hydrocarbons has been for high vapor pressure materials such as propane or butane. Although not always necessary, facilities for treating the stored material upon its removal from storage, such as dehydration equipment, have been usually installed. Since this type storage is adaptable to the storage of materials, other than propane and butanes, which do not require such facilities, no allowance for the facilities is included in the estimates.

4. Cavities by Mining

As with the other methods of storage, many limitations had to be placed upon the assumptions used in arriving at comparative estimates for the construction of cavities by mining. In general, after the exploration work is completed, one might expect the cost of construction of underground storage by mining, provided the storage is constructed in an impermeable formation, to vary between $2 and $8 per barrel of capacity dependent upon a number of factors such as depth, thickness of formation, difficulties such as water bearing formations through which the shaft must penetrate, etc.

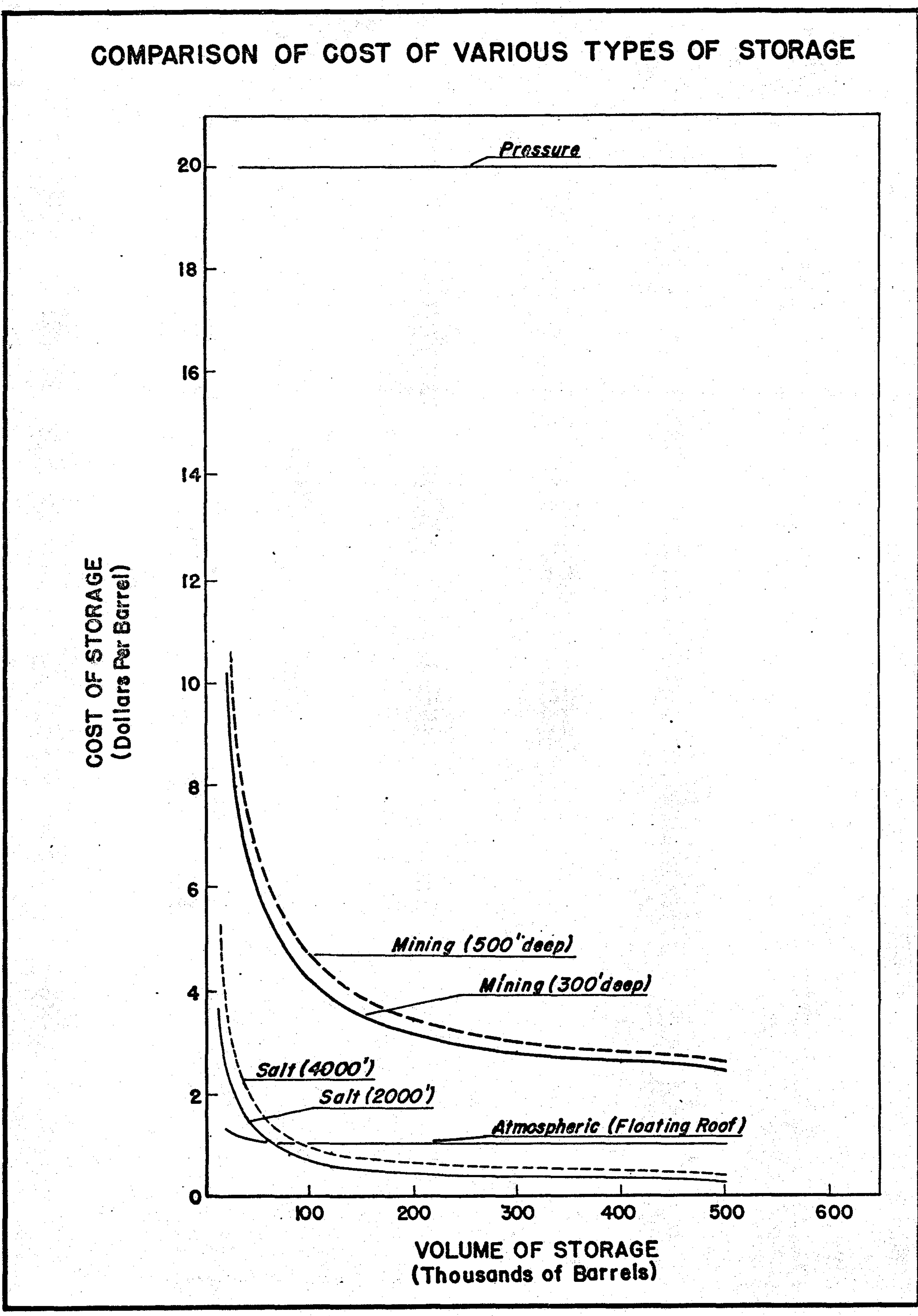
In arriving at the comparative estimates reflected in Plates I, II, and III, since the cost of geological exploration, including the cost of core test holes, will vary extremely from locality to locality and to effect a common denominator for comparative purposes, an estimate of such cost is not included in the prepared estimates. As with estimates made of other methods of storage, it was presumed that a site was available near current existing loading racks and no additional surface storage is required to effect appropriate utilization of the storage.

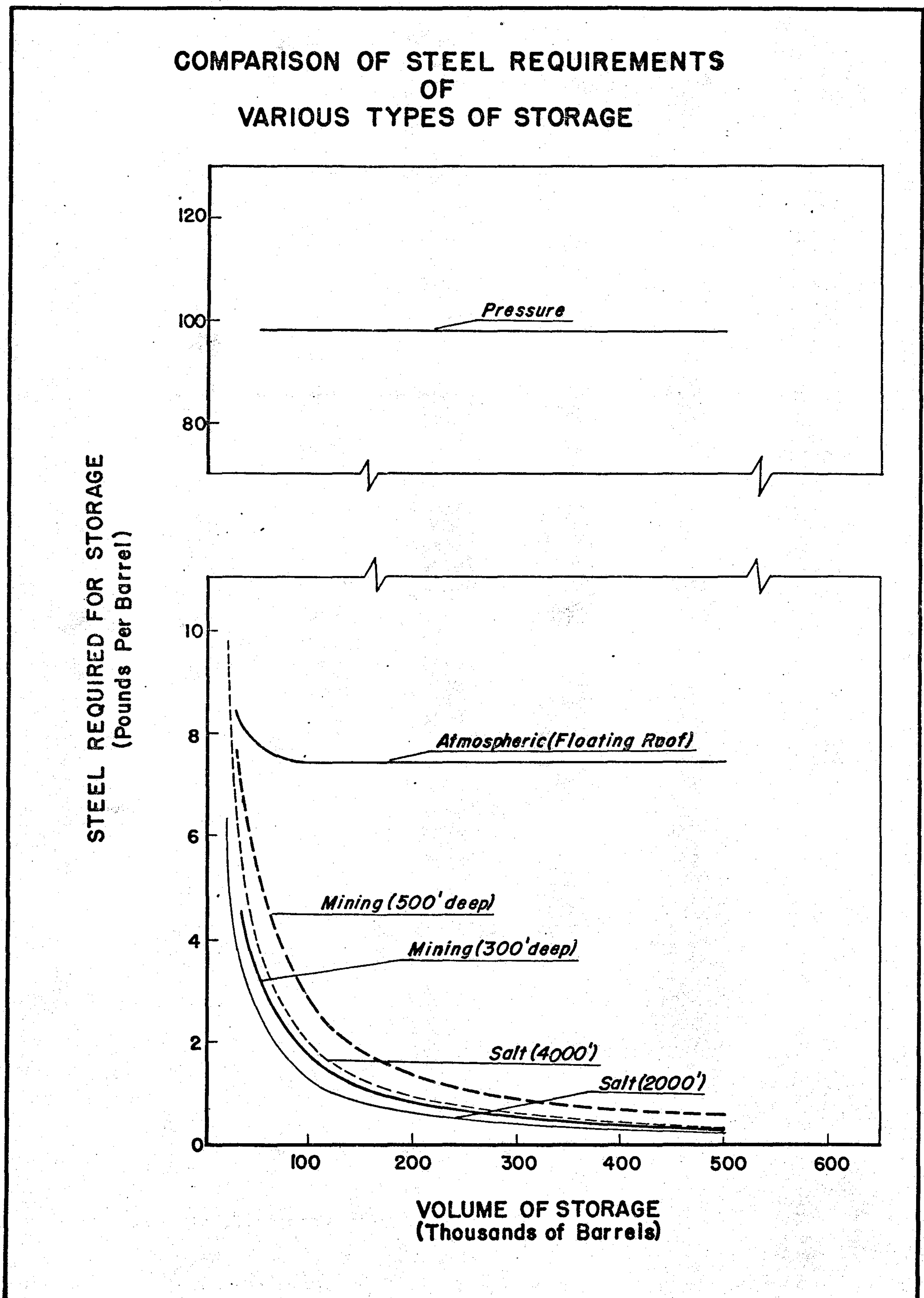
In preparing the estimates, it was presumed that little difficulty would be experienced with sinking a shaft to the appropriate depth. The presence or absence of harder rocks, such as granites, were not considered a problem since with current mining techniques, the additional costs to penetrate such formations are well within the limits of the estimates.

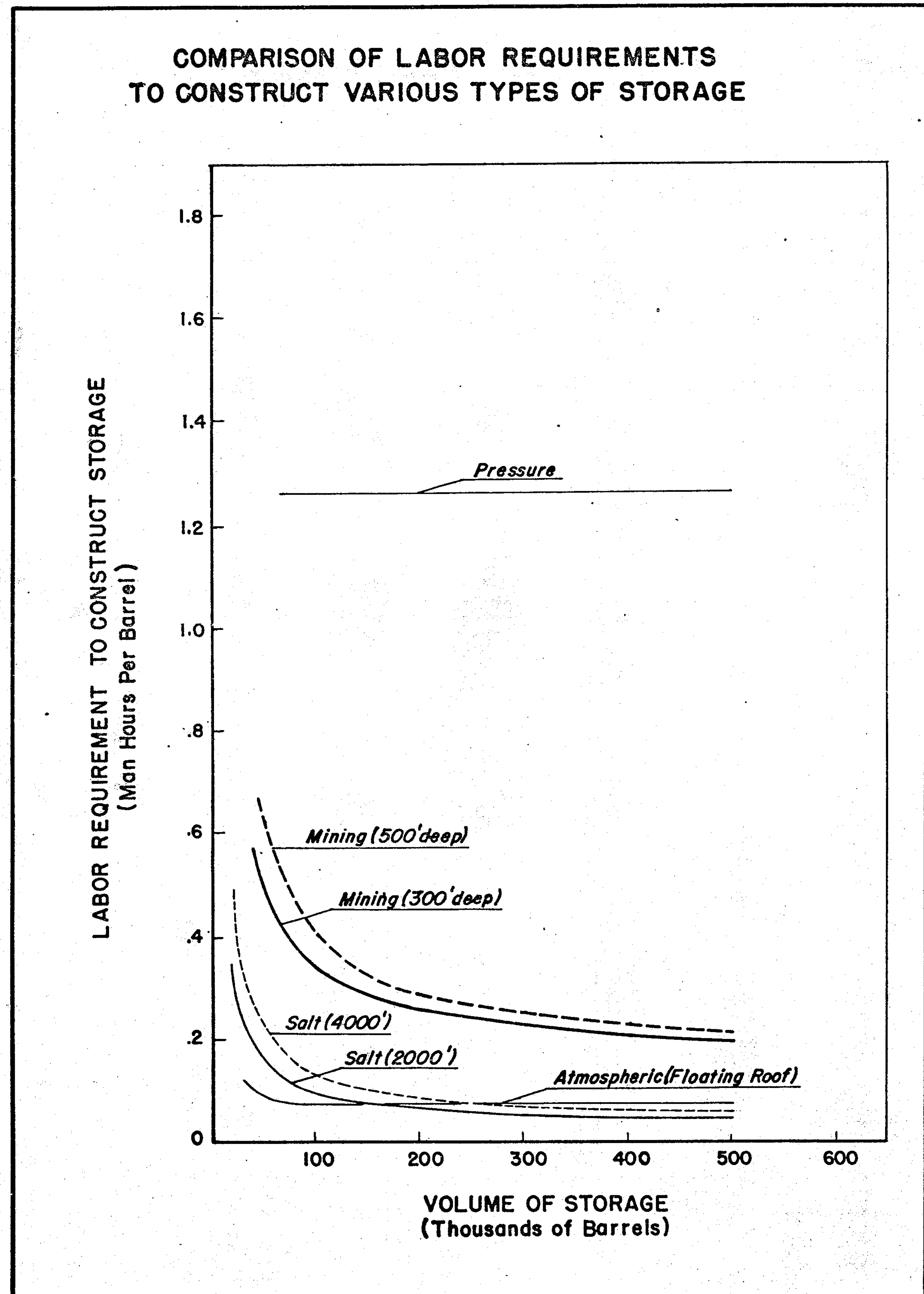
Once the shaft is constructed, the cost of excavating the cavity, within limits, on a per barrel basis varies little with the size of the storage or with the depth of the storage. In arriving at the estimates reflected in Plates I, II, and III, it was presumed that the formation thickness and characteristics were such that sufficiently large cavities could be effected from one shaft without undue subsurface handling of the mined material. In the construction of the larger storages, the subsurface space limitations are not as restricted as with the construction of small storages, making it possible to better utilize the subsurface use of material and labor.

Dependent upon the thickness and characteristics of the formation in which the cavity is constructed, for large storage, it may be an economic expediency to utilize more than one shaft. The estimates do not reflect this possibility. Care must be taken so as to conform to the mining laws and regulations within the particular state so as to provide appropriate safety for personnel, such as additional shafts for vents, etc.

It cannot be assumed that all storages created by mining are initially pressure tight. The ways and means of correcting any leakage which might occur is considered an individual project problem, the cost of which will vary widely between individual storages. Appropriate initial exploration, coring, and testing should control the specific location of an underground storage project so as to minimize the possibilities of leakage.


COMPARISON OF COST OF VARIOUS TYPES OF STORAGE
Pressure
Mining (500' deep)
Mining (300' deep)
Salt (4000')
Salt (2000')
Atmospheric (Floating Roof)
COST OF STORAGE
(Dollars Per Barrel)
0
2
4
6
8
10
12
14
16
18
20
100
200
300
400
500
600
VOLUME OF STORAGE
(Thousands of Barrels)


COMPARISON OF STEEL REQUIREMENTS
OF
VARIOUS TYPES OF STORAGE
STEEL REQUIRED FOR STORAGE
(Pounds Per Barrel)
120
100
80
Pressure
10
8
6
4
2
0
Atmospheric (Floating Roof)
Mining (500' deep)
Mining (300' deep)
Salt (4000')
Salt (2000')
100
200
300
400
500
600
VOLUME OF STORAGE
(Thousands of Barrels)


COMPARISON OF LABOR REQUIREMENTS
TO CONSTRUCT VARIOUS TYPES OF STORAGE
LABOR REQUIREMENT TO CONSTRUCT STORAGE
(Man Hours Per Barrel)
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
Pressure
Mining (500' deep)
Mining (300' deep)
Salt (4000')
Salt (2000')
Atmospheric (Floating Roof)
100
200
300
400
500
600
VOLUME OF STORAGE
(Thousands of Barrels)

Appendix IV

PARTIAL BIBLIOGRAPHY

SWEDEN

Storage Project

Feldspar mines used for oil storage in Sweden. OIL AND GAS JOURNAL Aug. 25, 1949. p. 90. See also ENGINEERING NEWS RECORD. April 19, 1951. pp. 56-57, and THE PETROLEUM TIMES (published in London, England) Feb. 22, 1952 pp. 140-141.

UNITED STATES

Storage Projects

Michigan.- Cities Service's Lowell project storing propane in massive salt. OIL AND GAS JOURNAL. Dec. 27, 1951. p. 101

Oklahoma-Texas.- Matheny, Frank. Underground storage for liquefied petroleum gases. PETROLEUM ENGINEER. Ref. Annual - 1951. pp. C-49 - C-52.

Texas.- Howard, K. C. The development and operation of LPG storage cavities in salt strata. JOURNAL OF PETROLEUM TECHNOLOGY. March, 1951. pp. 10-11, Sec. 1, and p. 3, Sec. 2.

Texas.- Johnson, Charles B., Jr. Underground storage of LPG, Carthage field, Panola Co., Texas. OIL AND GAS JOURNAL. June 8, 1950. pp. 50-52,70.

Texas.- Johnson, Charles B. "Underground Storage of Propane in a Salt Water Sand", Carthage Field, Panola Co., Texas. JOURNAL OF PETROLEUM TECHNOLOGY, Jan., 1951, Sec. 1, pp. 14-15.

Texas.- Matheny, W. F., and Billue, G. H. Underground storage tanks, in salt bed near Keystone Plant, Winkler County, Texas. CHEMICAL ENGINEERING Dec., 1950. p. 115.

Texas.- Reidel, John G. Texas Natural Gasoline Corp. obtains over 90% propane recovery from 50,000 bbl. salt reservoir, in upper Permian salt beds, Benedum field, Upton County. OIL AND GAS JOURNAL, April 19, 1951. pp. 167-168, 236, 237.

UNITED STATES (Cont'd)

Patents

Cooper, H.C.- Storage means for liquefied gas. 3,437,909, March 16, 1948.

Cross, R.- Water Mining Soluble Materials. 2,251,916, Aug. 12, 1941.

Hill, F.F.- Method for Storage of Petroleum in Natural Underground Reservoirs. 1,921,358, Aug. 8, 1933.

Kerr, A. N.- Underground Reservoir for the Storage of Liquefied Gases. 2,459,277, Jan. 18, 1949.

Pattinson, R.L.- Method of Storing Gases or Liquids. 2,590,066, March 18, 1952.