UNDERGROUND STORAGE

FOR

PETROLEUM

A REPORT OF

THE NATIONAL PETROLEUM COUNCIL

1957

UNDERGROUND STORAGE FOR PETROLEUM

A Report on the

INDUSTRY'S EXPERIENCE WITH UNDERGROUND STORAGE FOR PETROLEUM PRODUCTS

Presented by the

COMMITTEE ON UNDERGROUND STORAGE FOR PETROLEUM

on MARCH 7, 1957 *to the*

NATIONAL PETROLEUM COUNCIL

H. S. M. BURNS, *Committee Chairman*

NATIONAL PETROLEUM COUNCIL

OFFICERS

CHAIRMAN

WALTER S. HALLANAN, President
Plymouth Oil Company

VICE-CHAIRMAN

R. G. FOLLIS, Chairman of the Board
Standard Oil Company of California

SECRETARY-TREASURER

JAMES V. BROWN

The purpose of the National Petroleum Council is to advise or inform the Secretary of the Interior or the Director of the Office of Oil and Gas with respect to any matter relating to petroleum or the petroleum industry submitted to it by or approved by the Secretary or Director.

HEADQUARTERS OFFICE
601 COMMONWEALTH BUILDING
Telephone: EXecutive 3-5167

1625 K STREET, N.W. WASHINGTON 6, D. C.

UNDERGROUND STORAGE FOR PETROLEUM

TABLE OF CONTENTS

NATIONAL PETROLEUM COUNCIL
COMMITTEE ON UNDERGROUND STORAGE FOR PETROLEUM
(1955-56-57)

CHAIRMAN: H. S. M. Burns
Shell Oil Company
50 West 50th Street
New York 20, New York

SECRETARY: E. O. King
Shell Oil Company
50 West 50th Street
New York 20, New York

Hines H. Baker, President
Humble Oil and Refining Company
Houston, Texas

Paul Endacott, President
Phillips Petroleum Company
Bartlesville, Oklahoma

R. G. Follis, Chairman of the Board
Standard Oil Company of California
San Francisco, California

Jake L. Hamon
Dallas, Texas

W. Alton Jones, Chairman of the Board
Cities Service Company
New York, New York

R. L. Milligan, President
The Pure Oil Company
Chicago 1, Illinois

Sid W. Richardson, President
Sid W. Richardson, Inc.
Fort Worth, Texas

Sidney A. Swensrud, Chairman of the Board
Gulf Oil Corporation
Pittsburgh, Pennsylvania

Reese H. Taylor, President
Union Oil Company of California
Los Angeles, California

Wm. K. Warren, Chairman of the Board
Warren Petroleum Corporation
Tulsa, Oklahoma

TECHNICAL SUBCOMMITTEE OF THE NATIONAL PETROLEUM COUNCIL COMMITTEE ON UNDERGROUND STORAGE FOR PETROLEUM (1955-56-57)

CHAIRMAN: Russell S. Knappen
Gulf Oil Corporation
P. O. Box 661
Tulsa 2, Oklahoma

SECRETARY: E. O. King
Shell Oil Company
50 West 50th Street
New York 20, New York

Selection and Design

George R. Benz
Phillips Petroleum Company
Bartlesville
Oklahoma

S. G. Branyan
Anchor Petroleum Company
Atlas Life Building
Tulsa 3, Oklahoma

Construction

P. F. Dougherty
Sun Oil Company
Philadelphia 3
Pennsylvania

John McKenna
Warren Petroleum Corporation
P. O. Box 1589
Tulsa 2, Oklahoma

Operation and Maintenance

Harold A. Parker
Magnolia Petroleum Company
P O. Box 900
Dallas 21, Texas

N. E. Van Fossan
Texas Natural Gasoline Corporation
P. O. Box 1409
Tulsa 1, Oklahoma

Contamination, Deterioration and Alteration

J. D. Haney
Cities Service Research and Development Company
54 Wall Street
New York 5, New York

C. D. Norris
The Texas Company
135 East 42nd Street
New York 17, New York

Industry Advisers to Subcommittee

Douglas Ball
Ball Associates
1025 Vermont Avenue
Washington 5, D. C.

J. G. McNab
Esso Research & Engineering Co.
15 West 51st Street
New York 19, New York

UNITED STATES
DEPARTMENT OF THE INTERIOR
OIL AND GAS DIVISION

Washington 25, D. C.

C
O
P
Y

October 19, 1955

Mr. Walter S. Hallanan, Chairman
National Petroleum Council
1625 K Street, N. W.
Washington, D. C.

My dear Mr. Hallanan:

During the past four years there has been a significant increase in the amount of underground storage for petroleum products that has been developed and put in use by the industry. By this time the industry has information on the cost of underground storage compared to surface storage, and has experience as to the effectiveness of underground storage, product losses, and product contamination.

It is requested that the National Petroleum Council review the industry's experience with underground storage for petroleum products and submit such report and comments as the Council deems appropriate. It would be desirable that the report include information on the overall capacity of such storage now in use, by types, sizes, regional location and type of product stored, and the outlook for the increased use of underground storage.

Sincerely yours,

/S/ H. A. Stewart

H. A. Stewart
Director

REPORT OF
NATIONAL PETROLEUM COUNCIL'S COMMITTEE
ON UNDERGROUND STORAGE OF PETROLEUM PRODUCTS

INTRODUCTION

When the NPC Committee on Underground Storage issued its last report on April 22, 1952, it noted that through the normal operation of individual initiative there would probably be so much development of underground storage in the immediate future that a subsequent study would be mainly a record of achievement by the industry rather than a survey of possibilities and feasibilities. Such has indeed proved to be the case, because this new study, again executed by a Technical Subcommittee of the NPC Committee on Underground Storage, shows that underground storage in continental U. S. for liquid petroleum products now totals well over 25,000,000 barrels versus some 7,000,000 in 1952. The trade journals contain almost daily accounts of progress in underground storage.

It is found that, as might be expected, the expansion has been principally to handle Liquified Petroleum Gas, and such new storage has been constructed largely by washing out cavities in salt structures. There has, however, been a significant increase in the storage of LPG in mined cavities. These more expensive projects are the result of storage needs at refinery and plant locations, or because of industry's incentive to store transportation, as well as product, in areas close to the market. In such cases salt structures are not always available. As to the storage of less volatile hydrocarbons, the only project of significance (in industry and exclusive of government) is the storage of heating oil in a quarry at Wind Gap, Pennsylvania.

The Subcommittee has secured data on industry experience by sending a questionnaire to each known owner of underground storage. These projects together with their reported location, capacity (July 1956), and type have been plotted on a map which is included in this report and identified as Exhibit I. The same data are restated in tabular form in Exhibits II and III.

Besides collecting data on type, location, and capacity of underground storage, the Subcommittee, by means of its questionnaire, has also compiled industry's experience on the following technical aspects of underground storage: Site Selection; Design, Construction; Operation and Maintenance; Contamination, Deterioration and Alteration. The Contamination, Deterioration and Alteration aspect was further investigated by a study of unclassified information covering experimental work by the U. S. Air Force on underground storage of petroleum products. This was furnished by the U. S. Air Force, Air Material Command and Wright Air Development Center.

Each of the foregoing technical aspects has been analyzed and reported upon in detail in the final section of this report which comprises Appendices I to V inclusive. These appendices thus incorporate the experience of industry, as reported in the questionnaires, plus certain unclassified data of the U. S. Air Force, plus the latest engineering advice of the technical people on the Subcommittee.

The Subcommittee was divided into appropriate groups to investigate each of the technical aspects. Organization and membership are detailed on page iii. The Subcommittee had the advice of government observers from the Office of Defense Mobilization and the Departments of Defense and Interior.

It might be added that the excellent report on underground storage issued by the Interstate Oil Compact Commission in April of 1956 has added greatly to the over-all knowledge of this subject and, in particular, as to the geologic feasibility of underground storage in each of forty-two states. The Subcommittee has, of course, tried not to duplicate this report but rather to use it as a valuable reference work.

CONCLUSIONS

With proper site selection, design, construction, operation and maintenance, there is no question about the feasibility of underground storage, and its economics are attractive. The relatively low pressures involved in underground storage have posed no construction or operating problems that the industry is not already well qualified to handle through its experience in dealing with much higher pressures in usual oil field activities.

Underground storage is proving to be of substantial benefit to the Nation because it:

(a) protects supply continuity of LPG through better coverage of winter demands. Wider use is thus permitted of a convenient household, automotive and industrial fuel and petrochemical raw material.

(b) saves critical materials, notably steel, for other use in the national interest.

(c) permits better conservation of LPG because without such storage the gas would go to less economic uses.

Then too, industry's experience with underground storage may prove helpful to the military in planning for storage of petroleum products at strategic locations in a manner less vulnerable to enemy attack.

The Committee's conclusions as to what constitutes proper site selection, design, construction, operation and maintenance, plus experience with contamination, deterioration and alteration, are as follows:

SITE SELECTION

The geographic latitude in choosing an underground storage site depends largely on intended use and chemical and physical characteristics of the product to be stored. Acceptable sites may vary from a specific location to a large area in which many feasible locations are available. Published geological information is usually sufficient for tentative selection of an underground storage site, but a detailed geological study is necessary before final acceptance of the location.

This detailed study must include all horizons from the surface through the zone in which the cavern or reservoir is to be developed.

A number of additional considerations enter into the selection of an underground storage site. These include:

1. Availability of transportation facilities
2. Availability of utilities, including adequate water supply
3. Means of waste disposal (and possibly brine retention).
4. Proximity of conflicting operations
5. Surface conditions

DESIGN AND CONSTRUCTION

The successful completion and satisfactory operation of numerous underground storage caverns dissolved out of salt layers or domes or mined in shale or rock, and related auxiliary equipment, have shown that by the use of obtainable geological data, and with knowledge of the proposed operation, such underground facilities can be properly designed and constructed for the purpose intended, provided sound engineering standards and practices and considered experienced judgment are employed, with adherence to applicable regulations, laws, codes, etc. Experience has shown that the design and construction of such underground storage have provided the necessary safeguards to persons, property and product. A thorough knowledge of the underground formations is needed by the engineer to accomplish the suitable design and construction.

Although industry's experience has been almost entirely confined to storage of LPG, a few storage caverns and associated facilities have been designed and constructed for gasolines and burning oils.

OPERATION AND MAINTENANCE

The operation of underground storage terminals can generally be broken down into the following basic divisions of operations, their complexity being dependent on the type of cavity involved and the use of such storage:

1. Operational Scheduling (receiving, shipping and records; single tour or continuous operation).
2. Receiving, shipping and measurement (tank car, tank truck and/or pipeline).
3. Injection and Recovery (pumping, displacement, differential pressure, vacuum, waterflood, etc.).
4. Reprocessing (propane dehydration, free water knockout, and/or refractionation).

The operation of a solution type chamber, once it is properly constructed, is not particularly complicated. Comprehensive testing and maintenance programs, if properly planned and implemented, will minimize the possibility of serious difficulties or failure. Operating pressures are less than those associated with most producing oil and gas wells. Unrecoverable product losses are not generally excessive, ranging from 2% to 10% dependent on the type of construction and operational procedures.

The operation of a mined storage cavity, though slightly more complicated than the operation of a solution type cavity, is probably less expensive in out of pocket or direct operating costs. The unrecoverable losses reported ranged from 0 to 2%. The operating pressures are lower.

The operation of storage in depleted oil or gas reservoirs or in water sand sections is simply a matter of injection under pressure and recovery by means of formation pressure, water flood or vacuum. The losses are generally quite high and substantial amounts of recovered product must be handled in gaseous phase. Reported losses varied from 2 to 50%. Contamination of stored products is a serious problem.

Reported out of pocket operating costs, per unit volume of product handled in solution type cavities, ranged from $0.001 to $0.43 per barrel with no common basis for comparison quoted. Hypothetical out of pocket operating costs, per unit volume throughput, computed for a minimum and maximum installation (see Appendix IV, Figure A) on a common base, indicates a logical range of $0.15 to $0.80 per barrel throughput for the minimum installation and $0.10 to $0.70 per barrel throughput for the maximum, with intermediate installations lying somewhere between those extremes.

The problem of maintenance and repair of surface facilities supporting solution type storage reservoirs are not particularly unusual. The storage reservoirs themselves are subject to rather unique problems of maintenance and repair, the solution of such problems being within the scope of accepted engineering practices and the experience of the petroleum industry. The following difficulties have at one time or another been experienced by operators:

1. Failure of tubing strings due to tension, collapse or shear.

2. Plugging of tubing due to salt accumulation or insoluble precipitation.
3. Flotation entrapment of products.
4. Attrition due to corrosion.

Maintenance costs of mined storage cavities and related surface supporting equipment are less than that of a comparable solution type cavity installation because of the less severe corrosion conditions, the absence of flowing abrasive (and corrosive) liquids and the lower operating pressures.

The cost of maintenance on formation storage wells will be similar to normal oil field experience.

CONTAMINATION, DETERIORATION, AND ALTERATION

No contamination, deterioration, nor alteration has been encountered in storing liquefied petroleum gases and certain liquid hydrocarbons in solution cavities in salt domes or salt beds or in mined cavities in limestone, shales or in chalk. It may be necessary to dehydrate certain of these products on withdrawal from cavities to meet specifications.

The temperature of products stored in such cavities will be constant. This temperature will usually be higher than the average temperature encountered in above ground tankage; it will be much less, however, than the highest temperature reached in above ground tankage except in some salt domes in the Gulf Coast area.

The storage temperature in a cavity may usually be estimated by applying the commonly accepted geothermal gradient ($1^{\circ}F$ above the average atmospheric temperature for each 72 feet below the surface).

This will not apply, however, in regions where warm springs or hot water geysers are found, or in some salt domes located in areas near the Gulf Coast.

In other than such areas deterioration below ground will be appreciably less than in above ground storage. Products stored in cavities will also have a minimum of contact with or exposure to oxygen.

Butane, propane, and lighter hydrocarbons stored in depleted oil and gas sands, in water sands, or in stratigraphic traps are contaminated with residual crude oil and its dissolved gases, light gases, and free water. Products so stored and contaminated may require reprocessing.

No deleterious effect has been reported in the storage of heating oil in a covered reservoir in a slate quarry, where the liquid level in the reservoir is maintained at a level below that of the ground water table. Heating oils that may be mixed in such storage must be compatible.

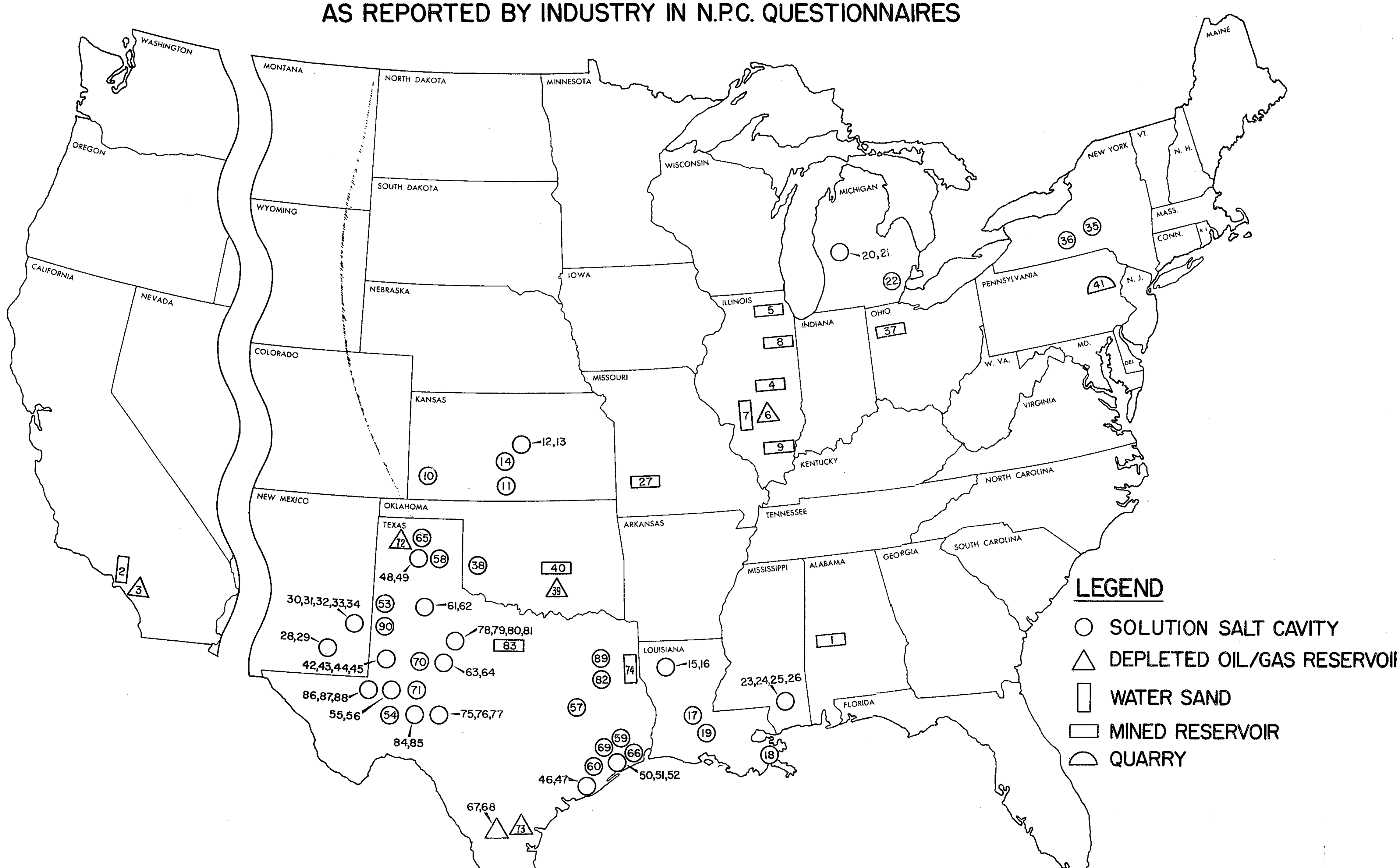
No deleterious effect has been reported in storing jet fuel or leaded aviation gasoline in dissolved salt cavities. Additives used must not be water soluble. It has been reported that unleaded motor gasoline has been similarly stored without deterioration. It can be assumed that leaded motor gasoline can also be so stored.

MAP REF.	PROJECT LOCATION COUNTY (CITY)	TOTAL PROJECT STORAGE CAPACITY (BBLS.)	NUMBER OF CAVITIES IN PROJECT	PRODUCT	TYPE OF STORAGE
	ALABAMA				
1	Sumter (Demopolis)	145,000	1	Propane	Mined Res.
	CALIFORNIA				
2	Los Angeles (El Segundo)	400,000	3	Propane, Butane, Olefin	Water Sand
3	Orange	50,000	1	LPG	Depl. Oil Res.
		450,000	4		
	ILLINOIS				
4	Douglas	171,400	1	Propane	Mined Res.
5	DuPage (Eola)	47,600	1	Propane	Mined Res.
6	Fayette	1,500,000	1	Propane & Butane	Depl. Oil Res.
7	Fayette	Not Rptd.	-	Propane & Butane	Water Sand
8	Kankakee (Kankakee)	260,000	1	LPG	Mined Res.
9	White (Crossville)	47,600	1	Propane	Mined Res.
		2,026,600	5		
	KANSAS				
10	Grant	131,521	6	LPG	Sol. Salt Cav. (BED)
11	Kingman (Rago)	225,000	3	LPG	Sol. Salt Cav. (BED)
12	McPherson	600,000	12	Propane	Sol. Salt Cav. (BED)
13	McPherson (Conway)	400,000	8	Propane & Butane	Sol. Salt Cav. (BED)
14	Reno (Hutchison)	450,150	8	Propane & Butane	Sol. Salt Cav. (BED)
		1,806,671	37		
	LOUISIANA				
15	*Bienville	368,000	4	LPG	Sol. Salt Cav. (DOME)
16	Bienville (Arcadia)	214,300	2	LPG	Sol. Salt Cav. (DOME)
17	Evangeline (Easton)	250,000	3	Propane & B-P Mix	Sol. Salt Cav. (DOME)
18	Plaquemines	200,000	2	Propane & Butane	Sol. Salt Cav. (DOME)
19	St. Landry	138,850	1	Propane	Sol. Salt Cav. (DOME)
		1,171,150	12		
	MICHIGAN				
20	Kent (Lowell)	163,000	2	Propane	Sol. Salt Cav. (BED)
21	Kent	100,000	1	Propane	Sol. Salt Cav. (BED)
22	Wayne	225,000	3	Butane	Sol. Salt Cav. (BED)
		488,000	6		
	MISSISSIPPI				
23	Forrest	420,000	3	LPG	Sol. Salt Cav. (DOME)
24	Forrest	200,000	2	Propane & Butane	Sol. Salt Cav. (DOME)
25	*Forrest	60,000	2	Propane & B-P Mix	Sol. Salt Cav. (DOME)
26	Forrest (Hattiesburg)	738,100	4	LPG	Sol. Salt Cav. (DOME)
		1,418,100	11		
	MISSOURI				
27	*Greene	25,000	1	Butane-Propane Mix	Mined Res.
	NEW MEXICO				
28	Eddy (Artesia)	71,400	3	Propane & Butane	Sol. Salt Cav. (BED)
29	*Eddy	48,000	2	Propane	Sol. Salt Cav. (BED)
30	Lea	300,000	3	Propane & Butane	Sol. Salt Cav. (BED)
31	Lea	115,000	2	Propane & Butane	Sol. Salt Cav. (BED)
32	Lea	86,000	2	Propane & Butane	Sol. Salt Cav. (BED)
33	Lea	84,395	2	Propane & Butane	Sol. Salt Cav. (BED)
34	Lea (Monument)	119,000	2	LPG	Sol. Salt Cav. (BED)
		823,795	16		
	NEW YORK				
35	*Cortland	150,000	1	Propane	Sol. Salt Cav. (BED)
36	Steuben	310,000	4	Propane & Butane	Sol. Salt Cav. (BED)
		460,000	5		
	OHIO				
37	Allen (Lima)	60,000	1	Propane	Mined Res.
	OKLAHOMA				
38	Beckham	17,505	1	Propane	Sol. Salt Cav. (BED)
39	Pontotoc	195,000	1	Propane & Butane	Depl. Oil Res.
40	Seminole	105,500	1	Propane	Mined Res.
		318,005	3		
	PENNSYLVANIA				
41	Northampton (Wind Gap)	1,000,000	1	Heating Oil	Quarry
	TEXAS				
42	Andrews	221,000	2	Propane	Sol. Salt Cav. (BED)
43	Andrews	58,000	1	Propane	Sol. Salt Cav. (BED)
44	Andrews	55,000	1	Propane	Sol. Salt Cav. (BED)
45	Andrews	50,000	1	Butane	Sol. Salt Cav. (BED)
46	Brazoria	771,000	3	LPG, Ethylene, Chemical	Sol. Salt Cav. (DOME)
47	Brazoria	600,000	3	LPG & Ethylene	Sol. Salt Cav. (DOME)
48	Carson	500,000	5	Propane & Butane	Sol. Salt Cav. (BED)
49	Carson	100,000	2	Propane & Butane	Sol. Salt Cav. (BED)
50	*Chambers	1,000,000	5	Butane	Sol. Salt Cav. (DOME)
51	Chambers	1,000,000	6	LPG	Sol. Salt Cav. (DOME)
52	Chambers (Mont Belvieu)	Not Rptd.	5	LPG	Sol. Salt Cav. (DOME)
53	Cochran	47,600	2	LPG	Sol. Salt Cav. (BED)
54	Crane	73,000	2	Propane & Butane	Sol. Salt Cav. (BED)
55	Ector (Goldsmith)	200,000	1	LPG	Sol. Salt Cav. (BED)
56	Ector	166,700	1	Propane	Sol. Salt Cav. (BED)
57	*Freestone	125,000	2	Propane & B-P Mix	Sol. Salt Cav. (DOME)
58	Gray (Pampa)	173,000	2	Propane	Sol. Salt Cav. (BED)
59	Hardin	465,000	4	Propane & Butane	Sol. Salt Cav. (DOME)
60	Harris (Houston)	1,000,000	3	Propane & Butane	Sol. Salt Cav. (DOME)
61	Hockley	68,000	1	Propane	Sol. Salt Cav. (BED)
62	Hockley	56,700	1	Propane	Sol. Salt Cav. (BED)
63	Howard	270,000	6	Propane & Butane	Sol. Salt Cav. (BED)
64	Howard	43,000	1	Olefin Feedstock	Sol. Salt Cav. (BED)
65	Hutchison (Borger)	1,200,000	10	LPG	Sol. Salt Cav. (BED)
66	Jefferson (Fannett)	605,000	4	LPG & Ethylene Gas	Sol. Salt Cav. (DOME)
67	Jim Wells	150,000	2	Propane & Butane	Depl. Gas Res.
68	Jim Wells	150,000	1	Propane	Depl. Gas Res.
69	Liberty	1,200,000	6	Propane & Butane	Sol. Salt Cav. (DOME)
70	Martin	290,000	6	LPG	Sol. Salt Cav. (BED)
71	Midland	238,100	4	LPG	Sol. Salt Cav. (BED)
72	Moore	2,500,000	1	LPG	Depl. Oil Res.
73	Nueces	85,000	1	Propane & Butane	Depl. Oil Res.
74	Panola	150,000	1	Propane	Water Sand
75	Reagan	1,500,000	10	Propane & Butane	Sol. Salt Cav. (BED)
76	Reagan	100,000	1	Propane & Butane	Sol. Salt Cav. (BED)
77	Reagan	42,471	1	Propane	Sol. Salt Cav. (BED)
78	Scurry	559,500	1	Propane & Iso-Mix	Sol. Salt Cav. (BED)
79	Scurry	146,750	7	Propane & Butane	Sol. Salt Cav. (BED)
80	Scurry	86,044	4	Propane	Sol. Salt Cav. (BED)
81	Scurry	64,300	2	Propane & Butane	Sol. Salt Cav. (BED)
82	Smith (Tyler)	750,000	3	LPG	Sol. Salt Cav. (DOME)
83	Stephens (Breckenridge)	60,700	2	Butane	Mined Res.
84	Upton	550,000	6	LPG	Sol. Salt Cav. (BED)
85	Upton	100,000	1	Propane & Butane	Sol. Salt Cav. (BED)
86	Winkler	145,000	1	Propane	Sol. Salt Cav. (BED)
87	Winkler	95,500	1	Butane	Sol. Salt Cav. (BED)
88	Winkler	60,000	1	Propane	Sol. Salt Cav. (BED)
89	*Wood	100,000	2	Propane & B-P Mix	Sol. Salt Cav. (DOME)
90	Yoakum	353,893	2	Propane	Sol. Salt Cav. (BED)
	Subtotal	18,325,258	141		
	Grand Total	28,517,579	244		

* Source: "Oil & Gas Journal" 7 / 16 /56

(BED) Cavity in Salt Bed
(DOME) Cavity in Salt Dome

UNDERGROUND STORAGE FOR LIQUID PETROLEUM HYDROCARBONS (EXCLUSIVE OF GOVERNMENT PROJECTS) LOCATION, CAPACITY AND PRODUCT AS OF JULY 1956 AS REPORTED BY INDUSTRY IN N.P.C. QUESTIONNAIRES



NUMBER OF STORAGE PROJECTS AS OF JULY 1956
UNDERGROUND STORAGE FOR LIQUID PETROLEUM HYDROCARBONS
LOCATION - PRODUCT STORED - TYPE RESERVOIR
SOURCE: N.P.C. 1956 QUESTIONNAIRES

PRESENT USE OF STORAGE*	ALABAMA	CALIFORNIA	ILLINOIS	KANSAS	LOUISIANA	MICHIGAN	MISSISSIPPI	MISSOURI	NEW MEXICO	NEW YORK	OHIO	OKLAHOMA	PENNSYLVANIA	TEXAS	UNITED STATES
Liquefied Petroleum Gas		1	1	2	2		2		1					10	19
Propane	1		3	1	1	2			1	1	1	2		14	27
Butane						1								4	5
Propane, Butane			2	2	1		1		5	1		1		14	27
LPG, Ethylene, Chemical														3	3
Propane & Iso Mix														1	1
Propane & B-P Mix					1		1							2	4
Propane, Butane, Olefin		1													1
Olefin Feed Stock														1	1
Butane - Propane Mix								1							1
Heating Oil													1		1
TOTAL RESERVOIRS	1	2	6	5	5	3	4	1	7	2	1	3	1	49	90
TYPE OF RESERVOIR															
SOLUTION SALT CAVITY				5	5	3	4		7	2		1		43	70
DEPLETED OIL RESERVOIR		1	1									1		2	5
DEPLETED GAS RESERVOIR														2	2
WATER SAND		1	1											1	3
MINED RESERVOIR	1		4					1			1	1		1	9
QUARRY													1		1
TOTAL RESERVOIRS:	1	2	6	5	5	3	4	1	7	2	1	3	1	49	90

* *Obvious overlap in product categories due to differing terminology used by companies when answering questionnaires.*

CAPACITIES (M BBLS.) OF UNDERGROUND STORAGE PROJECTS IN THE UNITED STATES (GOVERNMENT PROJECTS EXCLUDED) AS OF JULY 1956. SOURCE: N.P.C. 1956 QUESTIONNAIRES.

PRESENT USE OF STORAGE*	ALA.	CALIF.	ILL.	KAN.	LA.	MICH.	MISS.	MO.	N.M.	N.Y.	OHIO	OKLA.	PENN.	TEXAS	UNITED STATES
Liquefied Petroleum Gas		50	260	357	582		1,158		119					6,776	9,302
Propane	145		267	600	139	263			48	150	60	123		1,785	3,580
Butane						225								1,206	1,431
Propane, Butane			1,500	850	200		200		657	310		195		5,754	9,666
LPG, Ethylene, Chemical														1,976	1,976
Propane & Iso-Mix														560	560
Propane & B-P Mix					250		60							225	535
Propane, Butane, Olefin		400													400
Olefin Feed Stock														43	43
Butane - Propane Mix								25							25
Heating Oil													1,000		1,000
TOTAL STORAGE CAPACITY BBLS. AS OF JULY 1956	145	450	2,027	1,807	1,171	488	1,418	25	824	460	60	318	1,000	18,325	28,518

* *Obvious overlap in product categories due to differing terminology used by companies when answering questionnaires.*

APPENDIX I

SITE SELECTION FOR UNDERGROUND STORAGE

Purpose and Use of Storage

The geographic latitude afforded in choosing an underground storage site depends largely on the intended use and chemical and physical characteristics of the petroleum product to be stored. For example storage may be required to serve a specific producing plant. Ideally such storage should be on or adjoining the plant property. If such a location is impracticable, a more distant site connected to the plant by pipeline may be feasible. Underground storage designed to serve a specific point of consumption, such as a particular chemical plant or military base may have to be located within a very limited area. In contrast, storage intended to serve as part of a distribution system may permit a wide choice of sites. Perhaps in this instance the only requirement would be that the storage be located along a given railroad, highway or pipeline.

General Geological Considerations

After the geographical requirements have been resolved, the problem is to determine the types of storage that might be feasible for the area and to choose the most advantageous type if more than one is available. Geological data have been published for most areas of the United States in which underground storage might be desired. The National Petroleum Council's Report Of The Committee on Underground

Storage for Petroleum, (April 22, 1952), includes Plate I, a map which divides the United States into areas favorable or unfavorable for underground storage. The following areas are included:

1. Areas of Salt Domes
2. Areas of Salt Beds
3. Areas of Sedimentation (for mined caverns)
4. Granitic and Plutonic areas (for hard rock mines)
5. Sedimentary areas (where injection into porous rock may be possible)
6. Areas unfavorable for underground storage.

The Interstate Oil Compact Commission's report Underground Storage of Liquid Petroleum Hydrocarbons In The United States (April 1956), presents a more detailed study of subsurface formations suitable for storage. This report includes detailed geological information, applicable to underground storage, in 42 states.

The foregoing and other published geological reports provide a preliminary basis for selecting the storage site. The Underground Storage Committee has not felt it necessary to restate in this report, or attempt improvements upon, the regional geological data which is fully up to date and readily available from these sources.

Specific Geological Considerations:

After the general location has been chosen, a comprehensive geological study in the immediate area is necessary. Storage depth is an important factor. In general, great depths entail more investment and excessive power and pressure requirements for the movement of the product. Depth must be adequate, however, to insure sufficient strength in the overburden. The strength of the overburden must be adequate to contain the stored product at the maximum operating pressure. National Gasoline Association of America tentative standards require one foot of overburden per pound per square inch maximum operating pressure. This requirement applies to both storage in caverns and storage in porous formations.

The type and character of the formation in which storage is to be constructed must be investigated in detail. Pertinent points to be considered are:

1. Thickness of the Formation

   Thickness requirements in salt cavern storage are greater than in the case of mined caverns, where a network of lateral shafts may be utilized to develop the required storage capacity. The vertical height of storage chambers in salt beds usually range from slightly less than 100 feet to more than 500 feet. Vertical cavern height in salt domes is practically unlimited, and 1,000 feet of salt is commonly utilized in such projects. Thickness of the salt section is probably the most important single factor in determining the maximum permissible capacity per salt cavern well. In contrast operators reported lateral tunnel heights ranging from 20 feet to 38 feet in the case of mined caverns.

2. Permeability

   For cavern storage, an impervious storage zone is required to confine the product. In the case of storage in porous zones, permeability must be sufficient to permit rapid injection and recovery of the stored product. In this latter type operation, confinement is dependent upon the overlying (and perhaps underlying) formation.

3. Quality

Quality of a prospective storage formation is dependent largely upon chemical and physical purity and geological consistency. In the case of salt cavern storage, the amount and type of insoluble material in the zone is particularly important. In all types of cavern storage, consideration should be given to the possible existence of fractures, voids, seams, facies changes, and foreign material, such as gas and sulphur.

4. Structural strength

This consideration applies to cavern storage where the storage zone itself must form the sidewalls and may be utilized as the base and roof of the cavern.

Similarly, the type and character of the overburden warrant careful study.

1. Structural strength of the overburden is of extreme importance
2. The presence of voids, fissures and caverns in the overburden should be recognized, since these could cause serious leakage of product unless isolated from the storage zone.
3. The presence and character of gas, water, and other liquids, within the overlying formations are important

considerations in the storage program. Corrosive fluids above the storage zone warrant special protective measures.

Earthquake hazards should be evaluated prior to selecting underground storage sites. Surface terrain, although of secondary importance, sometimes has a bearing on the choice of locations. For instance, it may be necessary to place underground storage in swampland or on extremely steep hillsides. Although undesirable, such locations are sometimes unavoidable.

Transportation:

Adequate transportation facilities are required. These include one or more of the following:

1. Pipe lines
2. Railroads
3. Highways
4. Waterways

Utilities for Construction and Operation:

Important utilities include an adequate supply of water, fuel, and power. Water supply for dissolving salt caverns is most vital. Minimum requirement is in the order of 5,000 barrels per day for each active cavern, but considerably higher rates may be advantageous depending upon the desired leaching rate and the size of storage well casing and tubing. Total water consumption will probably range from seven to ten times the salt cavern capacity.

Choice of fuels and power is largely a matter of economics and availability. Natural gas, L P gas, and electricity are commonly used to meet the prime energy requirement. Three phase electricity is highly desirable however, for operating auxiliary equipment.

Waste Disposal or Brine Disposal and Retention:

In the case of salt cavern storage, it is necessary to provide a suitable means for disposal of brine during the leaching operations. Later it may become necessary to retain brine for displacement of the stored product from the caverns. In this general category, consideration should be given to both subsurface and surface disposal methods. In the case of mine caverns, a means to dispose of the spoil resulting from the excavation is needed.

Proximity to Other Operations:

In selecting a storage site, due regard should be given to potentially conflicting operations such as oil and gas producing fields, mining operations, and military installations.

General Considerations:

The art of underground storage has progressed to the extent that in most proven areas sites can be selected with reasonable assurance that the project will be completed successfully. Every site should be selected with the understanding that unusual or unexpected subsurface conditions (crevices, inclusion, or unexpected lithological changes), however remote, might require a change of plans. Calculated risks, analogous to those associated with the physical drilling for oil or gas, are inherent in underground storage. The risk and need for preliminary testing are greater for the untried area. Attention is directed to the fact that cores represent only a small sample of the formation under consideration. It has been reported that one project was abandoned, despite favorable coring results, when actual construction revealed that the prospective storage zone was unsatisfactory. It is encouraging, however, that underground storage has been highly successful despite occasional subsurface vagaries.

APPENDIX II

DESIGN OF UNDERGROUND STORAGE

Product to be Stored

In the design of an underground storage facility, the initial item to be considered is the type of product to be stored. As a general rule, high vapor pressure products require storage at a greater depth than that required by low vapor pressure products. Naturally, only very low vapor pressure products may be stored in open pits. Quality of stored product is the second function to be considered in the design of underground storage facilities. If it is a finished product which must meet certain specifications then design of the facility must incorporate features to avoid contamination. If a product that requires further processing is being stored, the initial investment and operating cost of the storage facility will be higher due to the cost of fractionation and/or dehydration facilities.

Preliminary Testing and Studies

In the design of underground salt caverns it is not necessary to make as comprehensive a geological and geophysical study as it is for mined underground storage. This is true because the assumption can be made that if salt is impervious in one hole at a location, it is impervious throughout that particular area. When drilling an underground salt cavern site for the first time, it is desirable to obtain cores to determine the amount of insolubles present in the salt and the location of any insoluble ledges. Formation pressure tests to determine formation permeability should be made before cavern development actually begins.

Since most mined storage is at relatively shallow depths and in formations which may not be uniform, extensive core drilling, core analyzation and formation pressure tests are required.

Geological Factors Requiring Consideration

The main geological factors to be considered in good design practice for an underground storage facility are: depth of a suitable formation; type and character of the formation at the storage depth; the thickness of the storage zone; permeability of the storage zone; the impurities in the formation zone which might result in product contamination; and strength and character of the overburden.

The Mode of Operation

Input

Rates at which product is to be received are of prime consideration in designing a cavern. Injection of product into an underground salt cavern is accomplished by pumping product into the outer string or casing of the well. Brine is removed through the tubing string. In the case of underground salt caverns, it is necessary to have larger tubing and casings at additional cost when injection rates are high. The pressure that is required on product which is being injected into an underground salt cavern is equal to that required to raise brine from the cavern to the surface, plus the pressure required to overcome resistance to flow of the product in the casing and of the brine in the tubing. These latter friction heads or pressures vary practically inversely with line size.

In the case of mined underground storage, where fill lines can be placed within the shaft liner, it is necessary only to increase the size of vapor connections at the surface for higher injection rates. However, spray loading may be necessary in order to keep temperatures and pressures within limits. The pressure required for product injection in a mined underground storage cavern is only slightly in excess of the vapor pressure in the cavern.

Withdrawal

Maximum withdrawal rates from salt cavities using brine or fresh water displacement are limited by the rate at which the displacement liquid can be pumped. The product is normally recovered from underground salt caverns by injecting brine or fresh water down the tubing string. Fresh water displacement of product is probably the most economical method of recovery from salt cavities; however, fresh water enlarges the storage cavern. Displacement of product by brine does not enlarge the cavern appreciably. However, brine storage ponds may be required. Submersible type pumps have been utilized to some degree but mechanical failures at critical emptying periods and high pump maintenance cost are distinct disadvantages.

Gas lift or vacuum system for product recovery from underground storage has a disadvantageous feature in that only a limited quantity of product may be removed if the storage depth is over a thousand feet. Where a product other than a finished product is being stored, gas pressure may be utilized for withdrawal.

Withdrawal rates from underground mined storage are limited only by the capacity of the pump and related piping. The two main types of product removal currently employed in mined underground storage are pumps and vapor lift systems. Two different type pumps are used; namely, submersible and deep well type pumps.

Safety Feature Considerations

Any underground storage facility should be protected from overpressuring. This can be accomplished by suitable relief valves on the fill lines or casing at the well head. In mined underground storage, relief valves designed to prevent overpressuring may be installed on the main shaft liner at the surface.

Overflowing of underground salt storage caverns can be prevented by installing any one of numerous types of automatic shutdown or alarm devices on the tubing or brine line from the cavern. Gauging devices are usually provided in the main shaft or vent holes in mined cavities to indicate the liquid level. In lieu of automatic shutdown or alarm devices, an operator may be stationed at the well-site to manually operate controls.

Design Standards

The design standards employed in the design of underground storage facilities should conform to appropriate standards including those issued by Natural Gasoline Association of America, American Petroleum Institute, National Fire Protection Association, Association of American Railroads, and to applicable local, state, and Federal laws and regulations.

Testing

Consideration should be given to testing the completed facilities in accordance with sound engineering practices and applicable standards and regulations. The effectiveness of cement and casing seals should also be tested.

Other Design Considerations

The design should provide a means for removing equipment while caverns are in service. In the case of mined underground storage, consideration should be given to providing a means for removing or repairing pumps without having to shut down operation of the cavern. Tubing shears or failures in underground salt storage may occur after the cavern has been filled with product. Since water is heavier than the product being stored these caverns may be emptied by dropping either fresh water or brine through the product and flowing the product out even though the tubing may be sheared.

The shapes of underground storage caverns in salt formations may be controlled by the addition of floating liners or protective strings or hydrocarbon protection blankets. Nearly any desired shape can be obtained in dissolving underground storage caverns by proper use of hydrocarbon blankets and protective strings.

Economic Factors Affecting Design and Construction

A. Type of product to be stored.

1. Vapor pressure.
2. Permissible impurities.
3. Disposal of non-condensable gases.
4. Dehydration of product, if required.
5. Fractionation of product, if required.

B. Geology of formation above storage formation.

1. Lost circulation zones.
2. Water bearing zones.
3. Heavy ground.
4. Structural strength.
5. Surface terrain.
6. Disposal of dissolved or mined spoil.
7. Depth to storage formation.
8. Proximity to other mining operations.

C. Size of storage.

1. Well spacing (applicable to solution storage only).
2. Completion time.
3. Thickness of storage formation.
4. Stability of formation.
5. Roof rock.

D. Method of product removal.

1. Fresh water.

<u>Economic Factors Affecting Design and Construction</u> (Continued)

D. Method of product removal (Continued)

2. Brine.
3. Vapor lift.
4. Submersible pump.

E. Operational rates required.

1. Large volumes -- large casing for salt -- big pumps on cavern.
2. Small volumes -- small casings.

F. Storage costs.

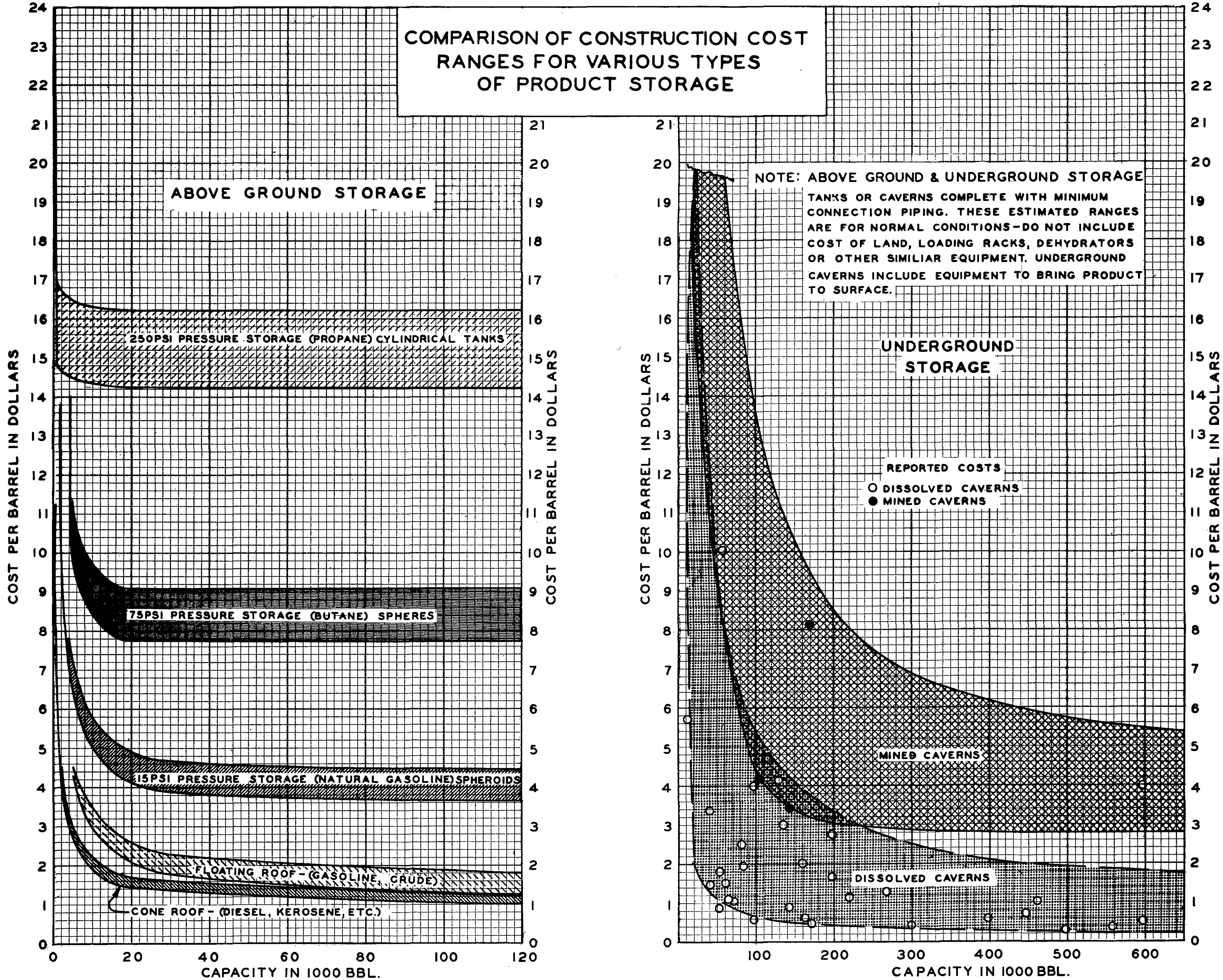
Figure A shows a comparison of estimated construction cost ranges for underground and aboveground storage of hydrocarbons.

The underground storage estimated construction costs are for mined caverns and for cavities dissolved from salt domes and salt beds. Reported costs are indicated.

Aboveground storage estimated construction costs are for steel storage tanks of the types commonly used for storage of low pressure fractions -- crude oil, heating oil, motor fuel, natural gasoline fractions, etc. -- and for liquefied petroleum gases.

From the chart it may be seen that for products such as butane and propane, underground storage is more economical than aboveground storage when large quantities are to be stored and where conditions are such that underground storage can be constructed. Also, where conditions for underground storage are favorable and real estate costs are high, underground storage for normal liquid hydrocarbons such as motor fuel may be economically favorable.

Estimated cost ranges shown are for comparable and normal conditions for both underground and aboveground storage. The cost ranges include minimum connection piping but do not include cost of land, loading racks, dehydrators, or other similar equipment; however, underground storage cost ranges do include equipment to bring product to the surface.


COMPARISON OF CONSTRUCTION COST RANGES FOR VARIOUS TYPES OF PRODUCT STORAGE
ABOVE GROUND STORAGE
250PSI PRESSURE STORAGE (PROPANE) CYLINDRICAL TANKS
75PSI PRESSURE STORAGE (BUTANE) SPHERES
15PSI PRESSURE STORAGE (NATURAL GASOLINE) SPHEROIDS
FLOATING ROOF - (GASOLINE, CRUDE)
CONE ROOF - (DIESEL, KEROSENE, ETC.)
COST PER BARREL IN DOLLARS
CAPACITY IN 1000 BBL.
NOTE: ABOVE GROUND & UNDERGROUND STORAGE TANKS OR CAVERNS COMPLETE WITH MINIMUM CONNECTION PIPING. THESE ESTIMATED RANGES ARE FOR NORMAL CONDITIONS - DO NOT INCLUDE COST OF LAND, LOADING RACKS, DEHYDRATORS OR OTHER SIMILIAR EQUIPMENT. UNDERGROUND CAVERNS INCLUDE EQUIPMENT TO BRING PRODUCT TO SURFACE.
UNDERGROUND STORAGE
REPORTED COSTS
O DISSOLVED CAVERNS
● MINED CAVERNS
MINED CAVERNS
DISSOLVED CAVERNS
COST PER BARREL IN DOLLARS
CAPACITY IN 1000 BBL.

NOV. 15, 1956

APPENDIX III

CONSTRUCTION OF UNDERGROUND STORAGE

Within the scope of this phase of the report, construction is limited primarily to consideration of the methods and problems involved in creating the underground storage chamber since construction of the aboveground facilities is conventional. Further restriction is imposed to exclude considerations properly within the scope of the selection and design phase.

Methods employed in construction of underground storage facilities may be grouped into four general classifications:

1. Solution

   The creation of a storage chamber by dissolving the surrounding material with water.

2. Mining

   The creation of a storage chamber by removal of a suitable substance by conventional mining methods.

3. Utilization of Underground Reservoirs

   Suitable existing porous formations may be employed, i.e., a depleted oil reservoir subject to water drive.

4. Utilization of Existing Cavities

   Suitable existing cavities, i.e., caves, abandoned quarries, mines and tunnels.

A tabulation is presented illustrating the importance of each according to present reported utilization:

	METHOD	PROJECTS	CAVITIES	CAPACITY-BBLS.	% OF TOTAL CAPACITY
1.	Solution				
	(a) Salt Domes	21	69	10,205,250	35.8
	(b) Salt Beds	49	152	11,209,529	39.3
	Combined Total	70	221	21,414,779	75.1

	METHOD	PROJECTS	CAVITIES	CAPACITY-BBLS.	% OF TOTAL CAPACITY
2.	Mining				
	(a) Lime	1	1	25,000	0.1
	(b) Shale	7	8	752,800	2.6
	(c) Chalk	1	1	145,000	0.5
	Combined Total	9	10	922,800	3.2
3.	Utilization of Underground Reservoirs				
	(a) Abandoned Oil & Gas Wells	7	8	4,630,000 *	16.3 *
	(b) Water Sands	3	4	550,000	1.9
	Combined Total	10	12	5,180,000	18.2

* For proper evaluation of this figure it must be recognized that many operators interpreted storage capacity to mean total reservoir capacity rather than actual or usable capacity. Therefore, this figure is subject to considerable reduction for direct comparison to other types of storage, perhaps as much as 80%.

METHOD	PROJECTS	CAVITIES	CAPACITY-BBLS.	% OF TOTAL CAPACITY
4. Utilization of Existing Cavities				
(a) Storage * in abandoned rock quarry with a floating roof.				
	1	1	1,000,000	3.5
(b) Conversion of abandoned mines, tunnels, etc. - None reported.				
Combined Total	1	1	1,000,000	3.5
Grand Total	90	244	28,517,579	100.0%

* Now used only for light heating oil.

Evaluation of the above table indicates the importance of storage dissolved in salt structures which comprise about 75% of all underground storage and is almost exclusively devoted to light hydrocarbon storage. It is important to consider that experience in construction of underground storage is therefore primarily based on storage designed for LP-Gas.

DISCUSSION OF CONSTRUCTION METHODS

1. Dissolving Salt Structures

DRILLING

The drilling of a storage well is conventional and in most respects comparable to drilling an oil well, except in the casing program.

Presented for discussion purposes is a casing program designed to facilitate solution of most problems likely to develop under adverse or unknown conditions. A similar program might be employed where geological information is incomplete or adverse conditions are known to exist. In practice, a reduction or modification of such a program is frequently made and would be dictated by considerations of judgment, experience, and local conditions; this is particularly true in the case of salt bed wells.

String	Size O.D.	Depth
1	34"	100'
2	24"	500'
3	13-3/8"	1400'
4	9-5/8"	2000'
5	7"	2800'
6	4-1/2"	3000'

Total estimated steel requirements - 160 Tons.

Purpose of Casing Program:

String 1 - Surface casing.

String 2 - Set at top of cap rock. These sizes are selected as precautionary measures. In the event difficulty is experienced in the cap rock cavity, intermediate strings can be set through the cavity as required and insure that the 13-3/8" casing can be set through the cap rock.

String 3 - Set through the cap rock.

String 4 - Set a nominal 500' into the salt.

String 5 and 6 - These are suspended tubing strings permitting solution of salt to be confined to the lower section and effect desirable shape control.

SEALING

Sealing operations usually consist of cementing each string to the surface using common cement and additives as required by specific problems. For example, cementing of the 13-3/8" and 9-5/8" casing would utilize saturated brine slurry to prevent washout at the casing seat. Each cementing job is hydrostatically tested.

WASHING

Well washing operations, consisting of circulation of fresh water through the tubing strings, will proceed until the desired capacity of the well has been reached, or the well is required for storage. It may be desirable to control the rate of circulation to maintain high salinity of the effluent in order to maintain good shape control and in the interest of efficiency.

SHAPE CONTROL

Shape control and roof protection may be accomplished through the use of two concentric tubing strings and through the introduction of a hydrocarbon "blanket" into the well prior and during washing operations.

1. In most cases an upright, slender, conical chamber is considered to be ideal since this shape should provide maximum structural strength and roof protection.
2. In washing operations, the bottom of the smaller tubing string is positioned close to the bottom of the chamber and the larger string positioned perhaps 200 feet above

this point and, perhaps, 700-800 feet below the bottom of the cemented casing. This permits circulation of fresh water through the smaller tubing string with the brine returning through the annulus of the larger tubing, tending to confine the dissolving action to the lower section of the chamber. It also permits the use of reverse circulation as desired wherein the water is introduced into the chamber through the annulus of the larger tubing with the brine returning through the smaller tubing. As washing operations proceed, the position of the larger string of tubing can be changed to effect solution zone control. The reported utilization of the various methods of shape control in construction of existing storage is presented in the tabulation:

Utilization of Shape Control

Methods	Percentage by Volume
1. Two Tubing Strings	43.8%
2. Hydrocarbon "Blanket"	23.6%
3. Combination of #1 and #2	24.6%
4. No Control	8.0%
Total	100.0%

No information is available which permits more than a rough estimation of the maximum and minimum diameters of salt caverns produced for hydrocarbon storage. Estimates based on capacities and heights of existing caverns indicate a maximum diameter of approximately 130 feet and a minimum diameter of approximately 20 feet. It should be understood the above maximum figure is not intended as a limitation on diameter.

STORAGE

During storage operations, the use of two tubing strings may materially increase the flexibility of operations. As product is injected into the chamber, brine is displaced and returns to the surface through the tubing strings. Since brine return through both strings will permit injection at lower pressures, it may be considered desirable to lower the larger tubing to some nominal distance above the bottom of the smaller tubing prior to storage of product.

Assurance of continued operations is provided, for should the small tubing become obstructed, brine return can usually continue through the tubing annulus until it is convenient to clear the obstruction. Damage to the tubing resulting from sloughing of insoluble material, and consequent interruptions of operations, is probably less likely since the concentric tubing strings should afford greater structural strength.

In some localities, it is considered feasible to further enlarge the chamber, if desirable, as the product already in storage continues to function as a hydrocarbon "blanket". Solution could be continued, if necessary, until the chamber is filled with product down to the bottom of the larger tubing string.

PROBLEMS ENCOUNTERED

Difficulties experienced in washing wells consist primarily of:

1. Anhydrite or salt plugging the tubing.
2. Anhydrite and/or shale stringers or ledges sloughing off as the supporting salt is removed, which can deform, collapse, or break the tubing strings.

3. Build-up of insoluble materials, i.e., primarily anhydrite building up on the floor of the storage chamber resulting in plugging of the tubing.
4. A dead space dissolved above casing seat, which results in entrapment of stored product.
5. Possible vibration danger to well head, tubing, piping, etc., which may result from the use of reciprocating pumps, without pulsation dampers. This problem was not reported probably because operators have learned to prevent the problem developing.
6. Miscellaneous

The following table presents the frequency in which difficulties or hazards have been reported encountered:

FREQUENCY OF VARIOUS DIFFICULTIES

Method	Percent by Volume
Anhydrite or salt plugging the tubing.	6.6%
Anhydrite and/or shale stringers or ledges sloughing off, which can break tubing strings.	9.6%
Anhydrite building up on floor of storage chamber resulting in plugging of the tubing.	12.7%
Dead space dissolved above casing seat which results in entrapment of stored product.	12.3%
Miscellaneous.	1.8%
None.	57.0%*
Total	100.0%

*In evaluating the experiences reported, it is believed important to consider that although 57% volume of the existing storage was constructed without reported unusual difficulty, it is believed that most operators do not feel that such difficulties as anhydrite plugging of the tubing are unusual.

CORRECTIVE MEASURES

Corrective measures reported to have been employed in the construction of dissolved storage in salt structures consist of the following:

1. Utilization of two concentric tubing strings:
   (a) Reverse circulation.
   (b) Repositioning of tubing.
2. Utilization of hydrocarbon "blankets."
3. Maintaining storage chamber pressures well below hydrofrac pressures at all times.
4. Good drilling and construction practices.
5. Utilization of pulsation dampers with reciprocating pumps, or use of centrifugal pumps, to reduce or eliminate vibration problems.

The discussion under "Shape Control" has elaborated on the employment of the corrective measures tabulated and it is recognized that proper application of these principles and close supervision may minimize these problems as they arise, or tend to eliminate some problems altogether.

TIME

The time required to develop a salt structure storage well varies widely with local conditions, but for purposes of comparison, a typical storage well of 200,000 barrels capacity may require approximately nine months to complete; smaller storage, in salt beds, may be completed in less time, contingent upon local conditions and problems.

TESTING

Prior to the storage of product, the well should be tested in conformance with N.G.A.A. Tentative Standards for the Underground Storage of Liquefied Petroleum Gas - August 1952.

2. MINING

Accepted mining practices should govern construction of mined storage, and as such should present no unusual problems. However, specific problems encountered in the construction of mined storage consist of:

(a) Sealing off surface water sands before or during the shaft sinking operation.

(b) Properly sealing the completed shaft into the mined chamber.

(c) Strengthening the chamber walls, and roof, where spalling is present.

(d) Testing the completed storage chamber.

The solution of the aforementioned problems varies with the specific problems encountered, but adherence to good accepted engineering practice is required.

Construction of the mined storage should comply with the pertinent N.G.A.A. Tentative Standards for Underground Storage of Liquefied Petroleum Gas.

3. UTILIZATION OF UNDERGROUND RESERVOIRS

Accepted practices in development of this type storage should conform to conventional standards for drilling wells as described and applicable regulations.

4. UTILIZATION OF EXISTING CAVITIES

Development of this type storage is necessarily specialized and each case must be considered in view of applicable governing conditions and regulations pertaining to the specific project.

GENERAL SUMMARY

All practices and procedures followed in the construction of any underground storage should conform to applicable standards and regulations of the industry, local and national regulatory bodies having jurisdiction, N.G.A.A. Tentative Standards for the Storage of Liquefied Petroleum Gas, safety practices applicable and good engineering for such operations.

It must be recognized that, while general practices and procedures apply to all underground storage construction, each project, by reason of local geological conditions, will pose one or more specific problems peculiar unto itself and the solution of these problems will require considered, experienced judgment.

A. Mechanics of Operations

One of the most important functions of operations is the maintenance of accurate and current records of the volume of individual type products received, stored and shipped. There are, however, no practical methods presently available for gauging storage chambers, particularly solution cavities in salt sections. Positive displacement meters, compensated to a base measurement temperature and periodically proved, are the most reliable existing method of measurement, and then, of course, the contents or capacity of the chamber are determined only indirectly by measuring the difference between receipts and outgo.

Products may be received and/or shipped by tank car, tank truck, pipeline or manufacturing plant charge and recovery, dependent on design criteria and proposed usage.

Injection and recovery methods are dependent on type of storage chambers used. Displacement is almost universally used in the solution type chamber, i.e. when products are injected brine is recovered and when brine or fresh water is injected product is recovered. Either positive displacement or centrifugal pumps are used for injection and recovery. Centrifugal pumps are preferred because of their characteristics of non-pulsating flow and high rates in medium pressure ranges. Positive displacement pumps are used in high pressure, low rate installations; but maintenance problems are aggravated due to their pulsating flow characteristics, unless such pulsations are minimized by installation of dampers.

Storage in anticlines and depleted oil or gas reservoirs generally involves pressure injection. The reservoir fluids are either displaced or compressed. Product recovery is accomplished

APPENDIX IV

OPERATION AND MAINTENANCE OF UNDERGROUND STORAGE

OPERATIONS - GENERAL

A study of questionnaires, returned by members of the petroleum industry utilizing underground storage as an integral part of their operations, indicates that this type storage is being used to advantage for four basic purposes:

1. Plant Storage - manufacturer or producing plant stocking products for wholesale outlets in large quantities. Mostly butane, propane and LPG.
2. Process Storage - user of liquid petroleum products as charging stock or raw material to manufacture petrochemicals or other products.
3. Local Marketing and/or Large Distribution Terminal Storage - for wholesale and retail markets.
4. Pipeline Surge Space - for use in emergency such as supply plants shutdown, terminal plant shutdown, or pipeline shutdown, and/or accumulation of products from various points of limited production for large scale pipeline movements.

A discussion of the various types of underground storage used by the petroleum industry is included in the section of this report entitled Construction.

by pressure recovery method carried out either by water flooding through offset wells, gas lift, or vacuum recovery.

Injection of products to mined chambers is usually accomplished by low pressure high volume pump injection or by differential pressure (temperature) movements. Product is recovered by deep well pump or differential pressure.

The problems of contamination, deterioration and alteration are discussed in the section of this report of the same title. In the event that reprocessing is necessary, the costs of such reprocessing of course will result in a higher cost per gallon throughput. Normally a solution chamber type storage facility will require propane dehydration equipment and entrained water knockout equipment on all recovery streams. The other types of storage, if propane is handled, will generally require some type of dehydration equipment.

B. Economics

When studies indicate the practicability of an underground storage installation, the economic analysis should, of course, be further extended to include the cost of operations. Cost of operations items will vary with company accounting procedures, and the usage and type of storage chamber, but generally can be broken down into the following components: (1) Maintenance and Repairs, (2) Supplies, (3) Utilities, (4) Transportation, (5) Salaries and Wages and Fringe Benefits,(6) Insurance, (7) Taxes, (8) Chemical and Treating Materials, (9) Office Expense and Supplies, (10) Laboratory Expense, (11) Communication Expense, (12) Safety Engineering, (13) Overhead, etc.

Operating expense itself is a widely variable figure, on a unit basis, because of the many different factors which affect its magnitude. In order to estimate the actual per-unit volume throughput cost of operations, it would be necessary to know the operating schedule. The cost would be drastically different for a continuous operation as compared to an intermittent one. Another important factor affecting the operating expense is the operating staff provided. Operating personnel are often a separate group for an underground storage unit; however, they can be combined with other operations such as plant or producing district, the labor cost being different in either case.

It is apparent that a certain minimum volume throughput must be handled to bring the cost per unit volume throughput to a bearable figure. Generally speaking, the "cost of operations versus volume throughput" curve is relatively flat i.e. with operating schedules, maintenance and repair (as applied to corrosion and attrition rather than mechanical deterioration), insurance and taxes fixed for a particular installation. It costs very little more to handle 700,000 bbl. than 500,000 bbl.

C. Operational Difficulties

The annual cost of storage will be increased by costs incurred due to lost time, loss of utilization, loss of products and cost of workover, repair or replacement. Various operational difficulties can be anticipated, but the incidence and degree of severity of these difficulties cannot. The more usual and reoccurring of these difficulties will be discussed in the latter portion of this report.

D. Safety Precautions

A well rounded inspection, maintenance and testing program should be established for an underground storage installation.

A fire and disaster plan are necessary for personnel and public safety. First aid and fire fighting training programs for company personnel should be kept active. Up-to-date bulletins should be posted giving the name and phone number of company officials, key personnel as well as local authorities, hospitals, and doctors that may be called in case of emergency.

ACTUAL OPERATING CHARACTERISTICS AND EXPERIENCE FACTORS REPORTED BY OWNERS OF UNDERGROUND STORAGE PROJECTS

A. Solution Cavities

Mechanics of Operation

All operators reporting on this type cavity except one, used water displacement as a means of product recovery. One operator used a deep well turbine pump to recover product. Forty-five per cent of the operators reported the use of salt water for displacement of product, thirteen per cent reported using fresh water, twenty-one per cent reported using both fresh and salt water, and eleven per cent did not specify.

Economics

Of the companies that reported on operations of solution type cavities, only 27% gave an estimate of their operating costs; the reported operating cost per barrel taken from storage ranging from

$0.001 to $0.430 with no common basis for comparison quoted.

The innumerable variables involved in individual company accounting procedures, type of installations, labor force, work schedules, etc. tend to make both the maximum and minimum reported figures misleading. An attempt has been made (see Figure A page 63) to compute a logical range of "out of pocket" operating costs based on assumption of criteria quoted.

Eighty-five per cent of operators reporting indicated some stored product loss. Solution cavity operators reported losses ranging from 0 to 10%. It is extremely doubtful that products can be handled and stored without experiencing an average loss of at least 2% (measured at base temperature) of the total volume handled. Handling losses will vary with type of installation and number of times a product is handled, i.e. pipeline in / pipeline out handling losses will probably be less than truck in / truck out. Product losses in the cavity are generally recognized as unrecoverable product rather than loss to a foreign area. These losses will normally be large on initial filling, continue to be relatively large with fresh water displacement and decrease to a minimum with saturated brine displacement. This loss is generally attributed to flotation traps in the sidewalls of the cavity but can occur due to washout behind casing seat or off vertical product traps. Theoretically, the major portion of unrecoverable products could be recovered if the cavity were evacuated.

Operational Difficulties

Several operators reported tubing damage and breakage had occurred in wells in salt stratas due to sloughing of walls or caving of stringers. Two operators reported excessive accumulations of salt deposits in tubing which had to be cleaned out with fresh water. About 40% of the operators reported corrosion damage from brine water operation.

B. Mined Cavities

Mechanics of Operation

Eight operators of mined cavities reported their experience in the operation of this type storage. One reported the use of differential pressure to inject product. The other seven injected either directly from a plant or by use of conventional pumping equipment taking suction from surface storage or surge tanks. Four companies reported using compressors creating differential pressure to recover the product from the cavity and four reported using deep well pumps. All eight operators reported the use of above ground surge or storage tanks in their recovery operation. When propane was stored in mined cavities, operators reported the necessity of dehydration upon recovery.

Economics

Only one company reported a cost per unit volume throughput. This reported cost per barrel taken out was $0.714, which is $0.28 more than the highest unit cost for operating a solution cavity. Actually, the out of pocket operating costs per unit volume throughput in this type installation should be less than in a solution type cavity of comparable surface design and work scheduling. Two operators reported product losses. One reported less than 1% loss, and one reported a 2% loss. The other companies reported no loss. Initial filling losses should generally be higher and operating unrecoverable losses lower on mined cavities than on solution cavities.

Operating Difficulties

One operator reported excessive leakage around the perimeter of the bulkhead after about four months of operation. This difficulty was offset temporarily by flooding the shaft with water to a controlled level to provide a higher pressure than storage pressure on the inside of the bulkhead. The difficulty was later corrected by squeezing. Care is taken to maintain a slow injection rate during purging (on initial fill) to reduce the possibility of leaks caused from the refrigeration produced by vaporization of products at cavity conditions of temperature and pressure. A rapid drop in temperature will tend to cause contraction at the bulkhead and subsequent leakage.

C. Depleted Oil and Gas Sands

Mechanics of Operation

The use of a depleted oil or gas sand generally requires that plant process and compression facilities be available to recompress, reabsorb and/or refractionate stored products to specification. Seven such storage operations were reported in conjunction with plant operations for seasonal storage of light hydrocarbon products. The injection of product is done by conventional pumping equipment. This procedure increases the formation pressure.

The wells are produced by their own pressure as far as possible. At that time, vacuum recovery is utilized to obtain maximum product recovery. Most of the product is recovered in the gaseous phase and enters the process plant with the inlet gas stream.

Economics

The overall economics of an operation using oil and gas sands for storage of seasonal production of butane and propane is perhaps reasonable, if the products would otherwise be flared. The operating costs are not high if losses are neglected. Three companies report as follows:

Estimated Size in Bbls.	Depth, feet	Cost per Bbl. Taken Out
1,500,000	1,110	$0.822
195,000	3,284	$0.020
2,500,000	3,470	$0.120

Experienced losses reported by four operators follow:

Estimated Size in Bbls.	Depth, feet	Product Loss in %
195,000	3,284	50%
150,000	5,600	15-20%
150,000	6,600	2%
85,000	6,488	15.8%

Three of the reported operations have been taken out of service due to year around market demand for products taking all production.

Operational Difficulties

The main difficulty reported was contamination or dilution of the products with reservoir oils and gases. One operator reported freezing problems encountered when recovering product from the well.

D. Water Sands

Mechanics of Operation

Products are injected into reservoir by conventional pumping methods directly from the plant as produced. Product is recovered by natural water drive, water flood, or reservoir pressure. The water sands located at El Segundo, California have an active water drive which provides the energy to flow the product to the plant in the liquid state. Toward the end of the production cycle, in this instance, the water cut increases, resulting in a denser flow column in the tubing and consequently lower surface pressure. When surface pressure indication drops to a certain point, recovery procedures are stopped.

At Fayette County, Illinois the same method of production is used. A similar project was operated in Panola County, Texas, but the water was withdrawn when product was injected. Water was then used to reflood the reservoir through peripheral wells and the product produced from a well at the center of the reservoir.

Economics

The cost of operation of a water sand reservoir was reported by only one company and as being approximately $0.80 per barrel taken out. This cost does not include product losses, which appear to be relatively high compared to other types of underground storage. The reported product losses from water sand storage are tabulated below:

Estimated Storage Size	Depth in Feet	Loss in %
400,000 Bbls.	3,300 - 3,600	30-40%
?	1,200	90.31%
150,000 Bbls.	3,250	63.18%

One of these projects was abandoned when a year around market was obtained.

Operational Difficulties

Water encroachment during production cycle caused the operator in Illinois to cut back withdrawal rate so far that it was uneconomical to continue. When the withdrawal rates were increased, the water production increased, imposing a handling problem. No other unusual difficulties were reported in this type storage operation.

E. Open Pit Storage

The only reported storage operation utilizing open pits was at Wind Gap, Pennsylvania. Heating oil was pumped by conventional pumping equipment into abandoned slate quarry covered with a floating roof. In order to maintain the floating roof at a fairly constant level (4' allowable travel), it was necessary to pump water out at the same rate as the incoming oil plus seepage water. The water was stored in an adjacent quarry for recovery usage. The cycle is reversed when removing the oil.

Economics

This project is reported to be economical, with an operating cost of $0.23 per bbl. taken out and only a 0.3% product loss.

Difficulties and Precautions

Slight damage to the roof seal, caused from falling slate, was the only operating trouble reported. Below are listed safe practices that have been followed:

1. Normal safety standards that apply to bulk station operations.
2. The oil surface has been kept at a level lower than surrounding water table level to prevent oil losses.*
3. A secondary source of power has been made available in case of power failure during heavy rain storms.
4. A good public relations program has been maintained to keep local citizens well informed on nature of project. In this manner unfounded fears have been removed and the people assured that the project will not be detrimental to either the individual or the community.
5. Effluent water quality is checked periodically.

* If the roof were lifted above the upper limit, oil might be lost through seepage. Also, serious damage to the roof might result.

MAINTENANCE - GENERAL

A discussion of maintenance problems is an extremely important adjunct to the discussion of operations. Maintenance is a crucial factor in the out of pocket cost of operations; and if improperly analyzed or if neglected can swing the balance from a profitable operation to a short lived, and unprofitable one.

The basic unit of any underground storage installation is the storage chamber itself; and the only really unusual maintenance problems associated with underground storage are those associated with such chambers.

The maintenance problems of salt section cavities created by solution are of a more specialized nature than those associated with storage reservoirs in other formations. The major portion of this discussion will therefore concentrate on that type chamber.

Corrosion

Corrosion is definitely a problem in that its effect on the casing strings and surface equipment of the solution type cavity installations aggravates the maintenance problem thereby affecting the cost of operations. It is a fact, however, that the petroleum industry is faced daily with more extreme cases of corrosive action in some oil and gas wells, and has developed methods and processes that are highly effective in minimizing or eliminating damage.

Miscellaneous Maintenance Problems

Numerous other problems of maintenance resulting from attrition and accident are associated with the well head equipment, liners and tubing (as separated from the actual storage reservoir) of the storage well. It is normally presumed that maintenance becomes a function of operation at the completion of a construction phase; however, the actual construction procedures on the storage reservoir unit contribute to or minimize maintenance problems. It is invariably true that the tubing and liner strings will have to be pulled from the well on various occasions (due to plugging, necessity for making caliper surveys, etc.) during the construction phase. The pumping effect, water flows and abrasive material returns will also contribute to maintenance problems.

In the event that a positive displacement pump is used to wash the well, the surge associated with such pumps will tend to cause contraction and expansion in the tubing (and/or liner) string. If the tubing (and/or liner) is in contact with other pipe or in contact with formation, this contraction and elongation will cause a certain amount of abrasive wear which will be concentrated at the point of contact. Corrosion will also be accelerated at this point of good contact. Stress reversals will contribute to fatigue failure at thread roots. The surging (or jetting reaction) of flow from the end of the tubing will cause the tubing to jump and whip. Pulsation dampers properly designed and installed will minimize or eliminate this troublesome problem. Centrifugal pumps are not as troublesome in this respect. If the end of the tubing string is bent, some whipping action can occur even with a centrifugal pump.

A certain amount of insoluble, abrasive material is always present in salt formations. Good construction procedure dictates removal of these insolubles from the well as they are produced. Velocity flow of such abrasives contributes to wear. This abrasive wear will be most noticeable at points of restriction (high velocity) or change in direction of flow.

The rough and/or improper handling of tubing (and/or liner strings) during construction and workover jobs contributes to maintenance difficulties. The making up and breaking out of joints of pipe by use of power tongs, chain tongs or wrenches concentrates forces at one point which tend to crush the pipe. If the pipe is deformed its strength is reduced, the inside diameter is reduced (preventing the running of close tolerance tools) and if distortion extends into the thread area, it may contribute to leaks or may even necessitate discarding the particular joint. The very act of breaking out and making up threaded joints, reduces the life of such threads. If threads on both box and pin are thoroughly cleaned and doped with a good thread compound, before making up, wear will be minimized.

Pulling and running accidents are responsible for a number of problems. If the long, flexible tubing string contacts any obstruction while it is being run into the hole, it will be bent and conceivably no surface indication would be evident. Such bending may prevent running tubing the rest of the way in, make it difficult or impossible to pull the tubing, cause a focal point for insoluble bridging, or at the very least, give undesirable whipping action during water flow. If the tubing string is dropped, even for a short distance, extreme damage will result.

Maintenance of Well Head Equipment

The well head equipment (Christmas tree), since it supports liner and tubing, separates the various flows, and restrains the stored product, is one of the most important components of the storage unit. The bowl area for donuts (or slips) should be clean and free of corrosion and scoring. Packing on donuts (or slips) should be inspected and replaced when necessary to assure a pressure seal. Studs, gaskets, or ring joints of Christmas tree flanges should be protected by bands. Nozzles should be periodically inspected for abrasive wear. Valves should be properly lubricated and periodically inspected to evaluate effects of abrasion and corrosion.

Casing and Tubing Leaks

Product returns (during the storage phase) with displaced water generally indicate liner (or tubing) leaks. Leaks can occur at threads and collars or at point of corrosive or abrasive penetration. If product returns become excessive, the liner or tubing should be pulled from the well and the damaged joint or joints replaced.

Tubing failure (parting) in the product area will release some product to the surface. Parting below the product interface will be indicated by injection pressure drop. The former failure will necessitate cessation of injection; the latter failure will reduce the effective storage volume of the well. Tubing failure of this type is not normally associated with salt domes but can occur at any time in salt beds. General cause is insoluble stringer collapse possibly due to change in flotation effect between saturated salt water and stored products. The only remedial measure possible is to pull the tubing, clean out the bridge (if a bridge has been formed) and rerun tubing to bottom of storage chamber.

Tubing Plugging

Plugging of tubing during injection or recovery phase will cause a radical pressure rise on pumping equipment and stoppage of return flow. Plugging can take place at any time and is generally caused by accumulation of precipitated salt, insoluble fines, insoluble "boulders" or tubing collapse (without parting). This type failure (with the exception of collapse) generally takes place during the injection cycle. Salt accumulation on the inside diameter of the pipe returning supersaturated (at bottom hole temperatures) brine to the surface, is caused by cooling action of counter flowing cold product on the brine, thus reducing the brines' ability to hold salt in solution. This accumulation is indicated by a gradual rise of injection pressure over and above that normally anticipated. Accumulated salt may be washed or drilled out of the tubing.

Insoluble fines will be returned to the surface by the brine in varying degrees of concentration. If the concentration is high, and the injection procedure is shut down, these fines will settle back and, if a bridge is formed, will stack up and plug the tubing. If the concentration is low, the same effect can take place; however, a longer interval will be required for settling and a more radical focal point for bridging will be necessary. Salt precipitation coupled with insoluble returns creates a situation very susceptible to plugging. Bent or partially collapsed tubing will be a focal point for bridging. If the plug is short, increased pumping pressure below the plug may dislodge it and return it to the surface; if the plug is long, a pipe string can be run inside the tubing and the plug washed out of the way. A sand pump or hydrostatic bailer can sometimes be used to advantage in removing the plug. If the tubing is bent or collapsed (and the wash string or bailer cannot be run through the section) it should be cut off and enough additional tubing run to take advantage of the full volume of the storage chamber.

Cemented insoluble "boulders" may drop from the side wall of the storage chamber to the vicinity of the open end of tubing. Continual working of these boulders reduces them in size until they will fit inside the tubing. If the return velocity flow is sufficient these boulders will be returned to the surface. They have been known to plug valves (particularly if valves are not of the full opening type) on the Christmas tree. If they are not returned to the surface they can act as a check valve flapper and prevent back flow on the tubing during the displacement cycle or become the bridging point for insoluble fines accumulation during injection.

Setting tubing an adequate distance off bottom and displacing products from the storage well with saturated salt water will, to a great extent, eliminate stoppages due to insoluble fines or boulders.

Production Casing Leaks and Casing Seat Leaks

A planned, adequate and systematic testing program should be conducted on any storage cavity during the construction phase and continued throughout the operational phase. Such testing should detect any deviation from normal conditions in regard to the integrity of the storage cavity. Should static tests indicate some form of leakage, normal oil field procedures and processes will probably be adequate for locating and correcting of such failures.

Product Traps

Excessively large unrecovered product volumes after initial fill and recovery or after a secondary washing cycle indicates product loss to traps. A trap is any secondary cavity, large or small, which has been washed with such orientation that product, having entered the cavity, cannot return to the main storage chamber. A certain number of traps are invariably washed in any storage chamber. At least two major types of traps can lead to large volumes of products remaining unrecovered. If the production casing seat (in salt beds) does not have adequate structural strength (resulting in collapse) or if it is washed out (in either salt beds or salt domes) due to improper washing techniques or due to accident, a trap will be formed behind the casing. When product is injected into the well it will float up into this area and cannot drop back.

It then becomes unrecoverable product. If the initial bore hole is drilled with excessive deviation, an off vertical product trap will be formed, i.e., the washing water will rise vertically due to flotation and wash the chamber in the form of a trap. It is imperative that proper procedures be used in the construction phase to prevent the formation of these two types of traps. If an off vertical trap is formed a new bore hole may be drilled to intersect it. The off vertical trap is more likely to be formed in wells which utilize bottom hole washing without protective blankets but can be formed by major discontinuity in solubility of the salt mass and by major folding (without faulting).

Special Problems

It is clearly not within the scope of this report to identify and evaluate all the maintenance problems that can be associated with the solution type storage chamber. Only the major known problems of reoccurring nature have been covered. Each section of the country, and even each individual reservoir unit at the same terminal, will pose different problems. The problems introduced by earthquakes, collapse of casing strings due to shift or plastic flow, tension failure of casing due to major collapse of casing seat areas, washing into areas of high porosity and permeability etc., have not been encountered thus far and maintenance "estimate of the situation" and remedial action can only be taken at the time of occurrence. There can be no substitute for experience and no excuse for lack of thorough reconnaissance, exploration, selection, and design.

Any special equipment used in storage wells such as packer, perforated subs, side door chokes, washing jets, etc., should be studied carefully in the light of known corrosion effects, insoluble concentration in dead areas, salt precipitation due to pressure drop (and temperature drop) abrasive effect of insolubles and possibility of restriction of flow which would permit bridging by insoluble fines.

Equipment Maintenance

Preventive maintenance schedules and procedures for terminal equipment will be similar to any other installation utilizing equipment of a like nature. The same problems of packing maintenance, cavitation, over-ranging, minimum flows, priming, etc. will be associated with pumping equipment. Accumulation and flow of super fine suspended materials in products and brines will give some trouble. Electrical equipment, switch gear and other electrical contacts subject to brine sprays or mists will corrode. Product tanks on occasion will be charged with entrained water or full brine returns,and will have accumulations of super-fines. Tank blowdown (for removal of brines) should be a regularly scheduled task. Regenerative type dehydrators should be watched for condensation and packing, and proper scheduling provided for regeneration and recharging. Calcium chloride dehydrators should be closely watched for packing, carry over (to tanks and pipelines) and corrosion. Entrained water knockouts should be checked for fines accumulation, corrosion and proper automatic action. All buried piping should be adequately doped and wrapped and where necessary protected by cathodic means. Maintenance painting of exposed pipe and structures is a continual problem. Regularly scheduled lubrication of all valves and other equipment is most important.

Loading rack hose, swivels, valves, grounds and grounding reels should be inspected periodically and repaired or replaced when necessary.

Maintenance Problems on Chambers Other Than Solution Type

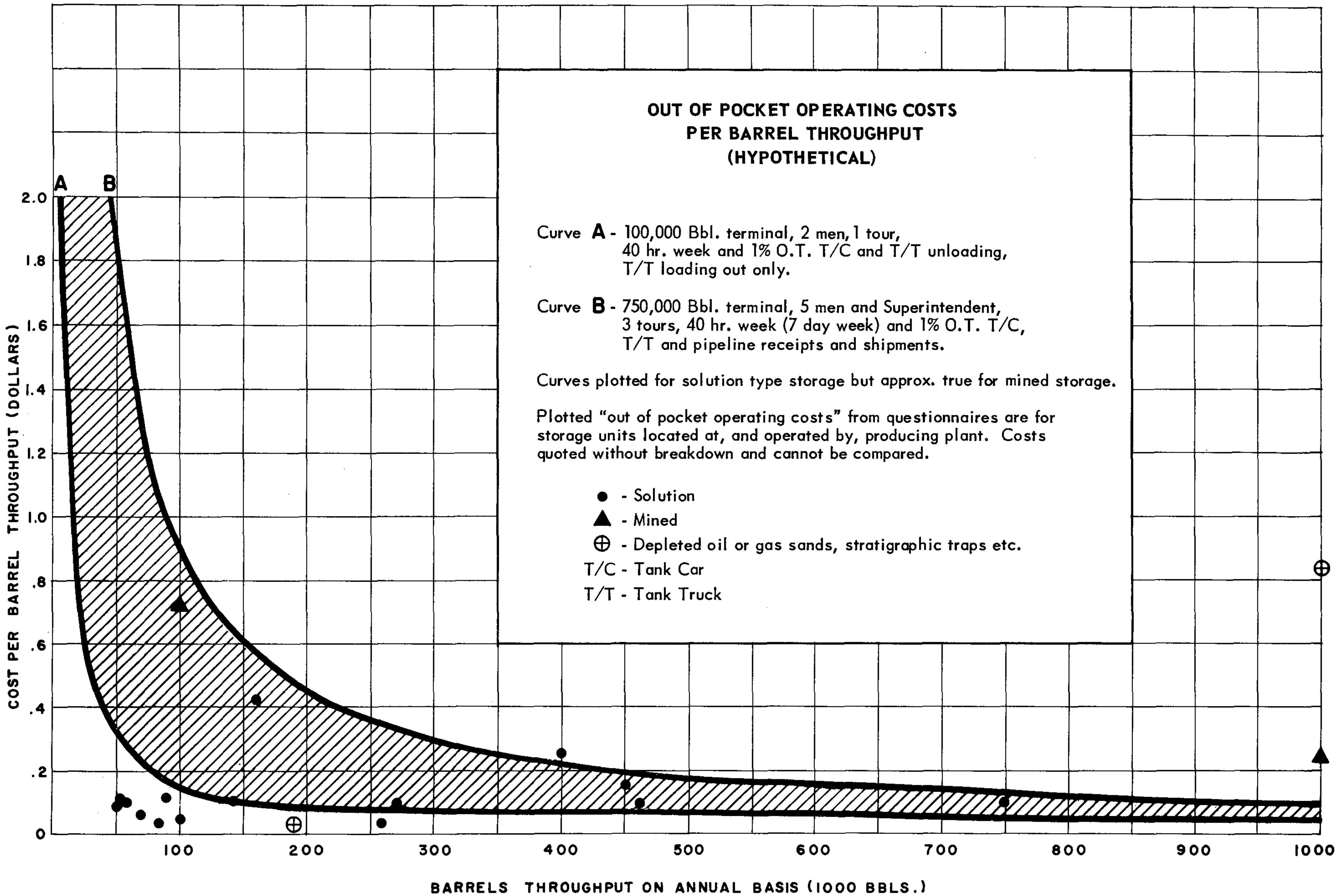
The maintenance problems associated with mined storage chambers (i.e., the actual chamber) should be relatively minor if every conceivable precaution has been exerted during the construction phase, to assure a leak-proof, stable, clean and properly graded chamber. The advantage of being able to construct a chamber to specification, visually inspect, test and reinspect, cannot be overestimated. The chamber is of known volume and not subject to hydrostatic pressures. The only flow involved is product flow under minor pressure. The problems of suspended solids should be minor. The problem of corrosion should be negligible. If bottom hole pumps are used the pump and pump column are not subject to outside influences. Water accumulation if present should be in small volumes, will probably be fresh water, and can be removed with minimum effort. Leaks behind the shaft lining (which is generally large outside diameter casing cemented to surface) should be detected during the testing phase and corrected prior to product injection.

One proposition should be firmly fixed in mind; repair work on the chamber interior, once product has been injected, is substantially out of the question.

The maintenance of surface equipment and facilities should be normal.

Surface storage (floating roofs on quarries, shallow mined chambers, etc.) for low vapor pressure products should be placed in the same category as mined chambers in regard to maintenance.

Anticlinal storage which has water or dry gas drive has not been used extensively and little is known about the maintenance problems involved. The basic problem would involve maintenance of the casing strings of injection and recovery wells. Needless to say, little could be done to improve the subsurface storage area or correct problems should they arise in that area. Surface equipment would be similar to storage terminals of other types except that high vapor volume returns would have to be handled. Problems of reprocessing would probably be critical and the maintenance of reprocessing equipment would be involved.



APPENDIX IV
FIGURE A

APPENDIX V

CONTAMINATION, DETERIORATION AND ALTERATION EXPERIENCE WITH UNDERGROUND STORAGE

1. Information Based on Questionnaires Returned:

A study has been made of some 83 questionnaires returned by members of the petroleum industry, reflecting their actual experience in the development and use of underground cavity storage of liquid petroleum products, principally liquefied petroleum gases. The findings are as follows:

A. Storage in Solution Cavities

Reports covering storage of liquefied petroleum gases and certain liquid hydrocarbons in over 200 solution cavities in salt dome or salt beds, having a total capacity of more than 20 million barrels, indicate that there has been no contamination, deterioration nor alteration from specification, resulting from such storage. Propane, however, recovered by water displacement method usually requires dehydration. This dehydration requirement appears to be a function of whether the propane is going through intermediate storage before sales. Where shipment is by pipeline or by water it is sometimes possible to omit dehydration.

Products reported to have been stored in solution cavities include:

Ethylene, Propane, Butane-Propane Mixtures, Iso Butane, Normal Butane, Normal Iso Butane Mix, Olefin Feed Stock (for Alkylation), Liquefied Petroleum Gas, LPG blends, and Natural Gasoline.

Except where a deep well pump has been installed in one of the cavities, products so stored are recovered by fresh water or salt water (brine) displacement. In most instances where propane is stored in solution cavities the product stream is directed through dehydration facilities and/or free water knockout equipment as it is withdrawn, to remove water of saturation and entrained water. This entrained water is picked up especially during the latter stages of propane recovery. At some solution cavities LPG, Butane, and Natural Gasoline streams are also directed through dehydrators.

In the 1952 report by this committee warnings were made against the possible contamination by sulphur, hydrogen sulfide, hydrocarbon gases, hydrocarbon residues, and carbon dioxide. Core samples, especially those taken in salt beds and in strata above the salt in salt domes are checked for such possible contaminants. Gases found in such samples, however, are usually eliminated in the process of washing the cavity. Reports on the 21 million barrels of such storage to date, do not reveal one case of such contamination.

B. Storage in Mined Cavities

Reports show that there are ten mined cavities containing Propane, Butane, and Liquefied Petroleum Gas, having a total capacity of about 900,000 barrels. All of these cavities are in either limestone, shales, or chalk. Experience with such storage has been reported to be as satisfactory as experience with solution cavities in salt formations.

Intensive study of core drilling records and examination of recovered cores is required in the instance of mined cavities particularly, to insure freedom from conditions which might promote polymerization, or from contaminants such as sulphur or iron in water.

It is necessary that Propane stored in mined cavities for specification deliveries, be dehydrated as it is withdrawn, especially at the initiation of any withdrawal. This is true whether the withdrawal is effected by the use of deep well type or submersible pumps, or by pressure differential built up between cavity and surface tankage by use of gas compressors.

C. <u>Storage in Depleted Oil and Gas Sands</u>

Propane, Butane and Liquefied Petroleum Gas stored in partially depleted oil and gas sands, usually located near a gasoline plant, is contaminated with reservoir water, residual crude oil and its dissolved gases. Products withdrawn from such storage must be reprocessed to obtain a specification product. These products are usually stored seasonally, withdrawn on demand, and reprocessed at the plant. Of the five such storages reported upon, one has been abandoned. The used capacity of the other four is reported as about 3 million barrels. (Refer to Appendix IV, Operation and Maintenance, for information on product losses.)

D. <u>Storage in Water Sands</u>

Propane, Butane and Olefin stored in separate water sands, having a total capacity of about 550,000 barrels (including 150,000 barrel project now abandoned) were reported to have picked up light gases, free water, and occasionally hydrocarbons, all in small quantities. Light gases and free water are removed in weathering drums. Small contamination of heavy hydrocarbons is removed by rerunning when necessary.

(Refer to Appendix IV, Operation and Maintenance, for information on product losses.)

E. <u>Storage in Stratigraphic Traps</u>

Liquefied Petroleum Gas (Butane and Propane) stored in a stratigraphic trap in sandstone having a capacity of approximately 1.5 million barrels is withdrawn in the vapor state, slightly contaminated by dry gas from the formation, and enters the gasoline plant ahead of the process section to separate Butane and Propane. Another such trap, capacity not determined, in which the same products were to be stored, was killed by water encroachment to the extent that withdrawals had to be made at an excessively low and uneconomical rate. A third such reservoir having a used capacity of 50,000 barrels has just recently been put in service. No withdrawals had been made from it at the time report was submitted. (Refer to Appendix IV, Operation and Maintenance, for information on product losses.)

F. <u>Storage in Abandoned Slate Quarries</u>

Heating oil is stored without contamination, deterioration or alteration in a reservoir formed by providing a steel floating roof in an abandoned slate quarry. An adjacent reservoir is used for the storage of water that is used to keep the liquid level in the first reservoir within limits for safe movement of the floating roof and below the ground water table. This slate quarry has a capacity of one (1) million barrels.

In such an installation the water should be checked to be sure it will not contaminate the heating oil, however, in this instance the water in adjacent quarry and adjacent streams is periodically checked for contamination.

A slight phenolic odor and taste was noted in the effluent water that was pumped from the oil quarry to the water quarry. This was eliminated by aeration and injecting water treating chemicals into the effluent water.

Heating oils delivered to this type of reservoir for long time storage, just as in the case of storage above ground in tanks, must be compatible with the oil with which they may be mixed.

2. Information From Other Sources

The information included in Sections A and B below was developed from study of unclassified information furnished by the U. S. Air Force, Air Material Command and Wright Air Development Center reports relating to Air Force experimental work on the underground storage of petroleum.

This material was made available on request by Captain W. R. Oliver, SC, USN, Chief, Industrial and Technical Branch, Petroleum Logistics Division, Office of the Assistant Secretary of Defense.

A. Storage of JP4 in Solution Cavity

Two batches of aircraft gas turbine and jet engine fuel, Grade JP4 were stored successively, in an existing underground salt cavern having a capacity of approximately 60,000 gallons (1,430 bbls.); one for a period of three months, the other for a period of 6 months, to determine the effect upon the quality of the fuel and the recovery that could be expected from such storage.

The chloride content of all samples taken from the cavern during these periods was 3.0 ppm or less. The fuel pumped from the cavern on completion of the storage periods did not contain sediment or free chlorides.

Specification analyses revealed that the fuel so stored did not change appreciably in chemical or physical characteristics. There was no deterioration of the fuel noted; no adverse effects of the fuel on a jet engine were observed such as salt deposits or corrosion, after an 80 hour test.

A special laboratory sample consisting of jet fuel with a 14.75% aromatic content was saturated with brine for 11 days at 77^{O}F. This fuel was then exposed to copper, lead, cadmium, steel, aluminum and magnesium for three hours at 212^{O}F and showed no corrosive effects on the metals.

The overall storage and handling losses were not considered excessive under the conditions of the tests. The storage and handling loss on the first batch of 1.16% included wetting and cavity hold-up loss which should not be recurrent. The loss on the second batch was only 0.7%.

B. Storage of Grade 100/130 Aviation Gasolines in Solution Cavity

Three batches of aircraft engine fuel or aviation gasoline for use in reciprocating type aircraft engines, Grade 100/130, were stored successively in the same underground salt cavern mentioned above (capacity approximately 60,000 gallons or 1,430 barrels), to determine the effects upon the quality of the fuel.

1. Approximately 50,000 gallons of Grade 100/130 fuel was stored in this salt cavern for a period of about 7 months. This fuel contained Tenemene #2 (NN' disecondary butyl paraphenylenediamine) as the oxidation inhibitor. Tests on samples withdrawn during this period evidenced no appreciable change in chemical or physical characteristics of the gasoline except for the dissipation of the oxidation inhibitor (Tenemene #2) and an increase in oxidation precipitate and potential gum. Subsequent labratory sample tests indicated that the depletion of the oxidation inhibitor in the fuel stored in the salt cavern was caused by the extensive circulation of the product prior to sampling. In subsequent tests the product was not circulated prior to sampling.

2. Approximately 40,000 gallons of Grade 100/130 fuel was next stored in this cavern for a period of about 7 months. This fuel also contained Tenemene #2 as the oxidation inhibitor. The oxidation inhibitor content was determined to be 0.9 lbs/5000 gallons of fuel. The inhibitor content dropped to 0.1 lbs/5000 gallons of fuel after approximately one (1) day in the cavern. Brine in the bottom of the cavern was acidic.

The effect of "amine" oxidation inhibitors is destroyed when the fuel is stored in the presence of acidic or weak alkaline aqueous solutions.

The abnormal dissipation of "amine" inhibitors can be precluded by controlling the pH of aqueous solutions in contact with the fuel at 9.3 or above.

Specification analyses of the Grade 100/130 fuel stored approximately 7 months evidenced that the material conformed to all the requirements of the product specification except the potential gum, after the 16 hour accelerated aging period. The product met the potential gum limits when the aging period was reduced to 5 hours.

3. Test results on Grade 100/130 fuel containing phenolic oxidation inhibitors stored in this cavern for a period of 10 months evidenced no appreciable depletion of the phenolic inhibitor and no significant change in the other chemical or physical characteristics of the fuel. Laboratory and field data generated indicates that a phenolic inhibitor (2, 6 - ditertiary butyl 4 - methyl phenol) in aircraft engine fuel is not adversely affected when contacted with solutions having pH range of 2 through 13.

C. Conclusions

On the basis of the above tests and the satisfactory experience reported it might well be expected that aircraft gas turbine and jet engine fuel, grade JP4, and aircraft engine fuel or aviation gasoline for use in reciprocating type aircraft engines, grade 100/130, can be stored in larger solution cavities in salt domes or salt beds or in mined cavities, without adverse effects, in locations where the storage temperature will not exceed the maximum allowable aboveground storage temperature for the same products. This conclusion is subject, however, to the oxidation inhibitor being insoluble in water. Further, it is assumed that none of the aviation fuels reported upon contained rust inhibitors. If the latter or any other additives are included in the fuel they are likely to be dissipated if soluble in water.

The same good judgement based on experience in the selection of sites, the construction or utilization of cavities and the safe handling of products, mentioned in the "General Conclusions" Section following, for the underground storage of liquefied petroleum gases and certain liquid hydrocarbons and the same intensive study of core drilling records and recovered cores, to assure freedom from objectionable contaminants or contaminating agents, especially in the case of planned storage in mined cavities, must be used in the selection and construction of underground storage for JP4 and Grade 100/130 aviation gasoline.

3. General Conclusions

The good results obtained to date in the underground storage of liquefied petroleum gases and certain liquid hydrocarbons in solution cavities and in mined cavities, as reflected in the reports reviewed are due in large part to the good judgment and experience of those responsible for the selection of sites, the construction or utilization of the cavities, and the safe handling of products.

One of the essential factors for a successful underground cavity, especially a mined cavity, is the intensive study made of core drilling records and the examination of recovered cores, to assure freedom from objectionable contaminants or contaminating agents.

Another factor is a thorough knowledge of the principal properties, and the chemical and physical characteristics of the product to be stored, the possible effect that storage over a long period of time at a predetermined uniform temperature, and at a higher pressure, combined with freedom from exposure to oxygen, may have on the quality and the performance of that product.

Still another factor is that additives in the product must not be water soluble where the product is subject, as is usually the case, to water contact.

The effect of temperature on product deterioration in underground storage can not be stated generally. The experience to date shows that the more uniform temperature below ground results in less deterioration than the same product would deteriorate above ground. This has been attributed to the fact that underground storage is at a temperature below the maximum temperature above ground. The data for these statements is based on the storage of C_4 Olefines, Leaded Avgas, Jet Fuel and Unleaded Motor Gasoline. The unleaded motor gasoline test was conclusive although details can not be furnished at this time.

Temperatures as high as 135°F have been reported for some salt domes in the Gulf Coast. Under such conditions it is expected that most finished products would deteriorate. Oven tests should be made before these domes are used for heating oils, diesel oils or gasolines.

Some companies have data indicating that storage of heating oils and diesel fuels at temperatures approaching 100°F will have some effect on their sales value, principally from color depreciation. There is no reason to believe that this condition would be aggravated by underground storage.

Products recovered from storage in depleted oil and gas sands, in water sands, and in stratigraphic traps normally have to be retreated and reprocessed.